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The Bear Island Cod: Migrations and Movements

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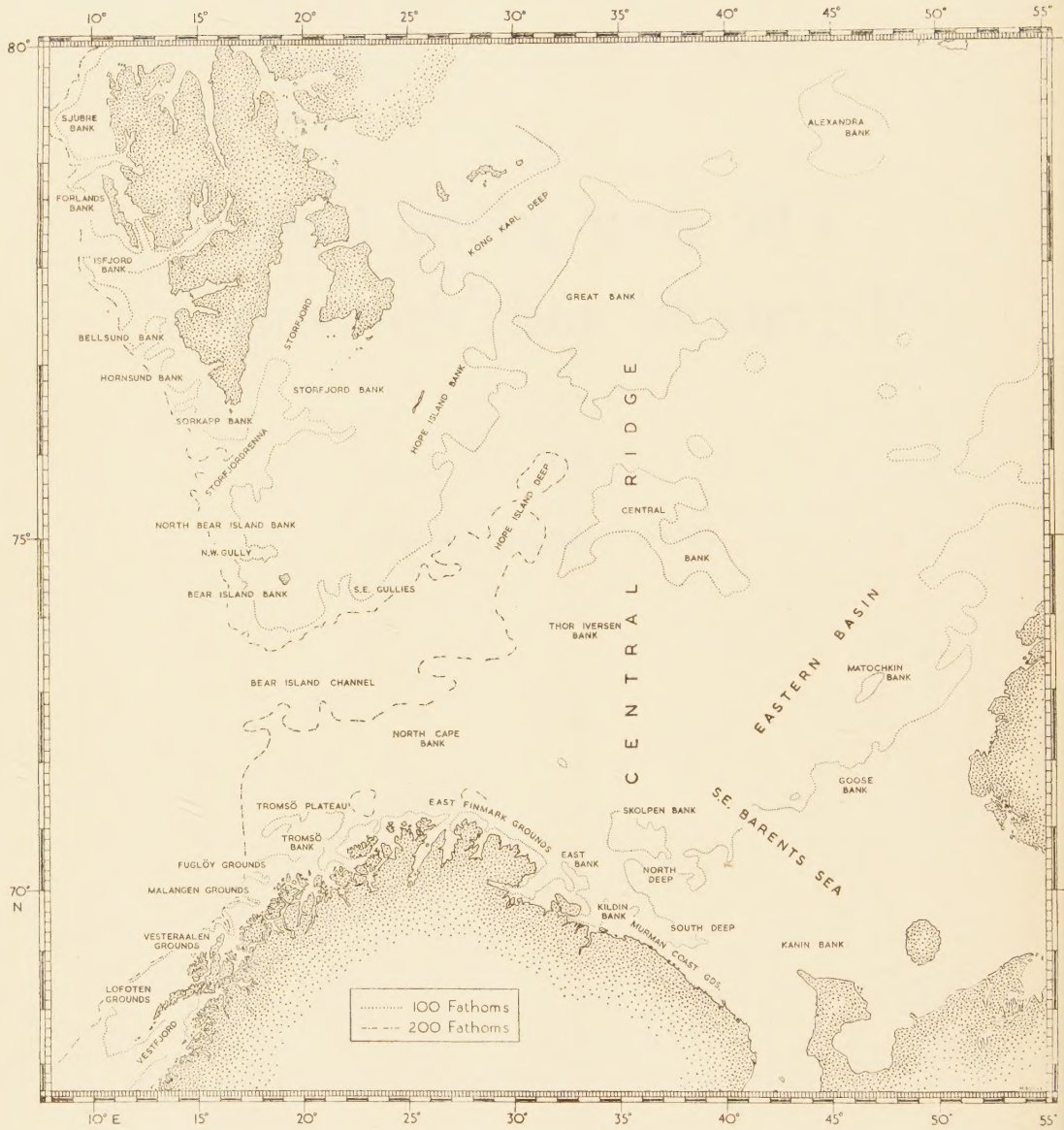

FIG. 1. *Chart of fishing grounds and place names of the Barents Sea.*

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INTRODUCTION

THE primary aim of this work was to study the movements of the shoals of cod at Bear Island, which are in the main immature and upon which the Bear Island fishery has been based since the early '30's. Migrations of the mature fish to and from their spawning grounds have long been known from the work of Hjort (1914 and 1926), Iversen (1934) and Dannevig (1947–50), and Idelson (1931). Messiatzeva (1932) and Maslov (1944) have contributed data from work carried out in more distant areas of the eastern Barents Sea. Little was known of the immature cod, however, but Russell (1937) considered that their movements were small and determined by their search for food, though Maslov (above) gave a schematic arrangement of immature cod migration, derived from length measurements made from trawlers at sea.

A knowledge of the shoals' movements is essential before an understanding of the causes governing concentration or shoaling of the cod can be obtained. It is obvious that the degree of concentration occurring in these shoals, which provide some of the most intensive fishing in the world, could not be the result of random movement. Some external factors which were considered likely to affect fish behaviour were therefore investigated.

Temperature has been thought to play an important part in the distribution of fish and fisheries and many authors since Le Danois (1924) and Beaugé (1932) have studied the relationship between bottom temperature and fish distribution, although as early as 1927, Awerinsew considered that the influence of water temperature might be indirect only. Cahn (1925) pleaded for a study of internal, rather than external, factors as being more likely to provide causative agents. These have been investigated, notably by Koch (1942), Fontaine (1946 and 1948) and Hoar (1951 and 1953) and it has been demonstrated that endocrinal cycles are related to migrational patterns.

Despite anomalies in the literature concerning optimal temperatures, that is, temperature ranges where the 'best fishing' might be expected, Thompson's study of the Newfoundland cod (1943) gave the initial direction to the work of the ERNEST HOLT at Bear Island. This has already been the subject of a progress report (Graham *et al*, 1954) whilst Lee (1952) described the distribution of the cod against the water temperature on the bottom of the Bear Island Bank. As a detailed study of bottom temperature and cod distribution is in course of preparation for the years subsequent to those dealt with in Lee's paper, temperature as an external factor influencing cod movement is omitted from this report.

Lee found that at certain times of the year, notably during the non-feeding period of November to June inclusive, an association existed between the distribution of the cod and the bottom temperatures of 2° to 4°C. However, it was obvious that temperature did not control their distribution, even during the non-feeding period, since there were expanses of bottom water of 'suitable' temperature in which, however, no cod were to be found. During the feeding period, July to October, feeding cod at commercial levels of catch were obtained in temperatures ranging from 5°C to − 0·5°C.

Concentrations of cod were frequently found associated with hydrographic features such as, for example, temperature gradients and tongues of water of a particular origin, but these features are not considered in themselves to be causative factors in the migrations of the shoals, although a cause and effect relationship for temperature has been assumed by many workers in this field.

Evidence is put forward, herein, of another external factor—light—which is shown to influence cod behaviour at certain seasons and thus, in conjunction with the cycle of water movement, to effect their horizontal distribution.

A well-known but little documented pattern of fish behaviour—that of an annual cycle of depth change—is put forward in a more quantitative form. This cycle has the effect of taking the cod from shallow banks where they spend the summer feeding and where water movement is mostly variable and affected by tidal flow, to the deeper waters of the continental slope, along which major oceanic currents run. Evidence is put forward which suggests that this annual depth change is the primary migration of the immature cod.

Whilst many details of the fishes' behaviour in the shallows are still to be elucidated —particularly the mechanism by which the migration to progressively deeper water is initiated—the general hypothesis put forward would appear to be applicable to other cod populations and also to other species of food fish which live under very different hydrographic and temperature regimes. The hypothesis runs as follows: distribution of the Bear Island cod results from the interaction of the cyclical flow of the West Spitsbergen Current and a change from the bottom living, winter, condition of the cod, to a diurnally pelagic phase, when daylight returns to the area in the spring.

A further result of this work was to demonstrate that the pattern of migration of the immatures is basically similar to that of the matures—without, of course, its culmination in spawning. It was found that with increasing age, the immatures' southerly winter migration approached in length that of the mature cod, as if, in the years immediately prior to maturity, they were making a "dummy run" towards the spawning ground. Previously Russell (*ibid*) had considered their early life to be more or less stationary upon the feeding grounds of the Barents Sea and that until maturity was reached no long migrations were undertaken.

As differences in structure of the otolith occurred in different areas, the otolith was an important tool in the first formulation of a rough and generalised pattern of movement of the June Bear Island shoals (Trout 1951, 1953, and Graham *et al*, 1954). Further incidental aims were to elucidate the alternating structure of the otolith and an investigation of the annual feeding cycle with which their structure appeared to be linked. Evidence is put forward which relates opaque zone formation to high level of food intake.

This paper is subdivided, therefore, into sections dealing with the original idea of the spread of the Bear Island shoals, derived from otolith studies on the immatures, and its testing by the direct method of tagging. Later sections deal with external factors, other than temperature, which were thought to be instrumental at certain times of the year in effecting both passive and active migration.

An attempt is made in the discussion to derive a generalised migration pattern and circulation of the cod in the Barents Sea as a whole, but as this investigation has been essentially one of movement, the quantitative aspects of tagging and the results of tag comparisons will be dealt with elsewhere. (Trout, in press.)

SECTION I

THE OTOLITH TYPES

WHERE large routine age composition data are required, age determination of the cod is carried out almost universally by means of the sacculus otolith. Unlike the thinner otolith of other gadoids, such as the hake (Hickling 1933 and Bagenal, 1954) or whiting (Bowers, 1954) the cod otolith is thick and so opaque that the annual rings cannot be seen in the whole state, except in very young fish when freshly removed from the sacculus.

Saemundsson (1923) viewed the cod otolith, by hand lens, after breaking it between finger and thumb, using reflected light. The fractured surface was seen to be composed of alternate opaque white rings and darker rings which appeared to be of a clearer substance. Such an appearance is given by reflected light to the unbroken gadoid and plaice otoliths (Wimpenny 1953), seen against a black background.

Rollefsen's development of the fracture technique included side illumination of the halved otolith, and viewing by low power binocular microscope at a low magnification.

The viewed face was shielded from direct light. The light beam thus struck the otolith approximately at right angles to the vertical axis, just below the shielded, viewed face. Some of the light was transmitted upwards through the half otolith and by this means the annual rings also appear as composite structures, of one dark and one light zone, but, by transmitted light, the dark or opaque zones of the cod are analogous to the white zones of the hake otolith, seen by reflected light, whilst the hyaline, or light zones, of the cod otolith are analogous to the dark zones of the hake seen by reflected light. All photographs of cod otoliths in this paper are by side illumination, i.e., by transmitted light and the terms opaque and hyaline alone will be used throughout. (*See also* Rollefsen 1933 and 1935.)

A Watson Greenough low-power binocular microscope was used, with × 5 wide angle eyepieces and a 54 mm objective. This optical equipment gave a magnification of approximately × 14 and enabled the entire otolith to be seen at one time.

The Spitsbergen Shelf cod otolith is essentially one containing a large nucleus or first year's opaque growth zone, inferring that it is the result of a long—5½ to 6 months—pelagic phase, instead of the 2½ months period obtaining in the North Sea population (Graham & Carruthers 1926). The writer has already shown (1954) that for the majority of Bear Island cod, of more than one year, the opaque zone is laid down during the period late June to October, when feeding is high and body growth and otolith growth are maximal. The hyaline zone is laid down between successive summer growth zones, i.e., from November to June—the 'non feeding period'—and may in this case be termed the 'winter' ring. It is of interest that body and otolith growth continue, though at a reduced rate, during the non-feeding period and the relationship between the laying down of opaque material in the otolith and level of feeding has still to be elucidated. This is discussed at the end of this Section, where more evidence is put forward relating opaque zone formation to feeding period.

In addition to the effectiveness of the fracture method for age determination, there is the further advantage that the microstructure of individual zones on the cross section may be seen directly, rather than through a varying thickness of overlying opaque material, as is the case with the otoliths of hake, whiting or plaice, when viewed whole by reflected light. Thus the structure of two consecutive opaque zones may be readily studied and compared. Furthermore it was possible to view simultaneously two half-otoliths in the same 'Plasticene' mount, to compare structures contained in the zones of two different fish.

Opaque zones of markedly different types were found in the otolith material collected by the ERNEST HOLT. These differences occurred both between individual otoliths and within the same otolith—suggesting that the cause must be environmental rather than genetical. There were three types of opaque zone structure, and in some otoliths all three types of zone were occasionally present. The following definitions were eventually decided upon:

Type 1

Opaque zones uniform in structure and in density of opaque material. Both margins of the opaque zone sharply delimited from the, typically, wide hyaline zone. It followed that otoliths with this type of opaque zone formation were extraordinarily easy to read for age. (Plate 1.)

Type 2

Opaque zones substantially similar to the first type except that there was in the middle, or near the middle, a thin hyaline zone which subdivided the opaque zone into two zones of approximately equal width, i.e., the opaque zone was 'split' by a hyaline zone. Occasionally there were more than one hyaline zone.

The hyaline zones or 'winter' zones between each 'split' opaque zone were well defined but on the whole gave the impression of being somewhat narrower. (Plate 2.) There was no difficulty in determining the age of these otoliths.

Type 3

Numerically less important was the otolith in which the opaque zone was wide and almost merged with the next. It appeared to be similar to that found typically in the Finmark

cod, which Rollefsen (1933) called the Finmark type. The Finmark cod, mostly immature —their length distribution, given by Sund (1939) compares closely with that of the June shoals of Bear Island—give rise to a great coastal fishery in April and May when they follow and feed upon the capelin *Mallotus villosus*. L. approaching the coast to spawn.

The hyaline zones could rarely be determined with certainty since the widths of supposed hyaline zones differed little from the widths of the hyaline matrix between successive opaque lamellae. Double hyaline zones also occurred. (Plate 3.)

Because of the geographical distribution, described later, type 1 was called the Western or W. type, having a more westerly distribution, whilst type 2 was called the Western (Split) or W(S) type. Finmark type otoliths were designated Eastern or E.

Indeterminates

A varying number of otoliths from each sample could not be ascribed easily to any of the three types defined above, but since the numbers of otoliths containing these was never large, they were included in the third category—the least important group numerically in the Bear Island area—for subsequent reclassification should this be considered necessary.

It soon became apparent that, although one otolith might contain two or more zone types, there was a certain sequence. Normally the first two, three or four opaque zones were of type 1, or type 3 and these were then followed by the split type (Plate 4). Occasionally the reverse occurred but this was less common.

At first, classification of an otolith was by the predominant type of opaque zone present in the otolith. This tended to be highly subjective and the obvious refinement of classification by means of the marginal opaque zone was introduced and the samples re-read.

In the early part of the year, and until August or even September, an otolith had to be judged on the opaque zone laid down in the previous year, since it was found that the 'split' or hyaline zone laid down in the second type of opaque zone was only completed by August or sometimes even early September, especially in older cod, such as first time spawners.

It was essential, however, to know whether these apparent differences were real, since they were based on visual criteria only and open to the criticism that the method of separation was subjective. Type specimens were photographed and using these as standards, otoliths having predominantly one type or other opaque zones were separated

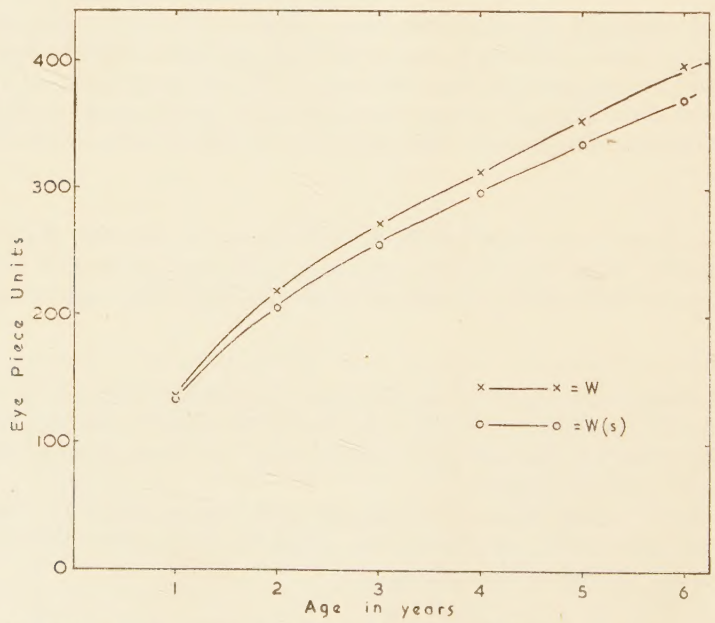

FIG. 2. *Otolith growth curve, of 'A'—axis only, of Type* 1 (*Western* = *W*) *and Type* 2 (*Western*(*Split*) = *W*(*S*)) *from mixed population at Bear Island, January–April* 1950.

from winter caught samples of fish, obtained from the southern Bear Island grounds—100 of each type W and W(S). Each otolith was cut across at right angles to its long axis and the successive zone widths of the viewed face were measured, as described earlier (1954). (These data, too numerous to publish, are available at the Lowestoft Fisheries Laboratory, where they may be consulted).

It will be seen from Fig. 2 that the otolith growth curve resulting from this visual separation of the otoliths indicates significantly different growth rates, although year by year the differences are not significant in themselves. Furthermore, comparison of growth of the cod bearing the two otolith types, even for the small number of fish used, showed that two different growth rates occurred in the shoals. The type 1 otoliths grew faster and their body lengths were greater than those of the 'split' type (see Table 1). Otoliths of the type 3 did not lend themselves to accurate measurement because of the difficulty of deciding where each year's opaque growth began and ended.

TABLE 1

Mean lengths in cm, of year classes from W & W(S) populations

Year Class	W	W(S)
1944	53·2 (26)	51·6 (34)
1943	65·3 (59)	61·6 (187)
1942	74·7 (25)	69·9 (56)

Summary of first 4 cruises 1950
(Figures in Brackets = No. of fish examined)

The existence of the two otolith types and two fish growth rates confirmed that (a) at least two sub-populations were present on the Bear Island grounds, in the June and October to December shoals; (b) that since the Bear Island grounds themselves did not appear to be important feeding grounds and the differences in the otoliths occurred during the 'summer' feeding period, i.e., July to October, the Bear Island shoals must separate after leaving the Island grounds and visit feeding grounds where the differing opaque zones were laid down; (c) since, too, each type of zone could appear in a given otolith, all the populations present had a certain degree of interchange. This was presumed to occur during the period when mixed shoals were on the Bear Island grounds, i.e., between November and June—although it was difficult to understand how Rollefsen's 'Finmark' type could be present at all. The general implication was that the populations were 'habitat varieties' or 'habitat races' and thus the otoliths might be used to obtain at least a generalised pattern of movement of the immature shoals.

It was with this hypothesis in mind that the percentage occurrence of each of the three otolith types was plotted for samples obtained away from the immediate neighbourhood of BearI sland. The charts in the following section give the mean percentage composition of groups of hauls in the areas fished, month by month during the years 1949–1950. In addition, selected cruises from later years are included to cover areas not visited in the first two years' work of the ERNEST HOLT.

SECTION II
GEOGRAPHICAL DISTRIBUTION OF OTOLITH TYPES

Before describing the geographical distribution of the different otolith types it is necessary to look at the general pattern of fishing which takes place in the Bear Island area—in the statistical division of the Barents Sea known as Region IIb. This is the area which lies north of latitude 73°N. and embraces all banks and grounds eastwards from the edge of

the Continental slope to Novaya Zemlya. In practice it covers grounds from SW. of Bear Island to the West Coast of Spitsbergen and east to the Central Bank and Great Bank (known to the trawler fleet as the Green Mud Bank). (See Fig. 1.)

The traditional English Bear Island fishery, which has built up since the early '30's, relates particularly to the months of May and June and is confined to the west side of the Bear Island Bank between the NW. Gully and the SW-ly grounds. This fishery tends to become highly concentrated, with between 30 to 70 trawlers operating within 20 to 30 square miles. On occasions several groups of trawlers are on different grounds and all experiencing high catches of medium sprag and codling. Fig. 3 gives the mean length distribution of June landings at Hull and Grimsby—the two main ports responsible for

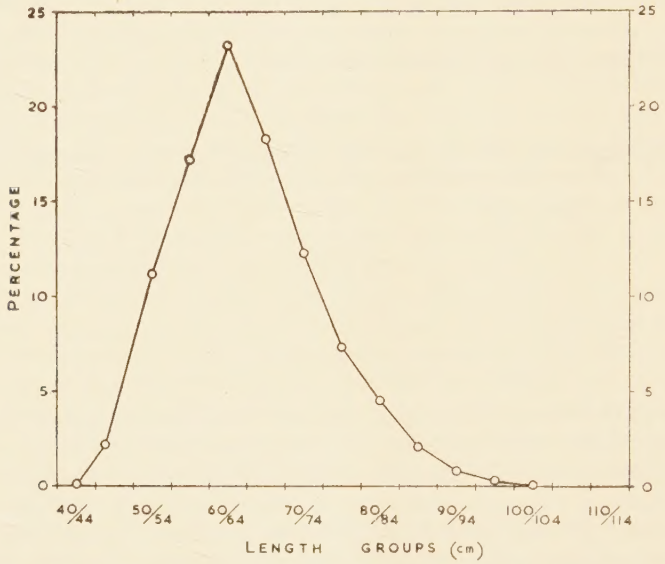

FIG. 3. *Percentage length composition of 'June' shoals at Bear Island.*
Mean of 1951–1956 Hull and Grimsby market measurements—but see also Table 2.

TABLE 2

Arctic Cod—Region IIb. Length distribution—June 1951–56

5 *cm Groups*	*June* 1951	*June* 1952	*June* 1953	*June* 1954	*June* 1955	*June* 1956	*Mean of six years* 1951–1956	5 *cm Groups*
	%	%	%	%	%	%	%	
40–44		0·5					0·1	40–44
45–49		9·5		2·4	1·4	0·4	2·2	45–49
50–54	4·4	31·3	4·6	13·9	11·9	4·7	11·2	50–54
55–59	13·9	19·7	19·0	19·4	26·6	13·6	17·7	55–59
60–64	27·0	10·1	30·4	19·4	25·3	25·4	23·1	60–64
65–69	23·1	8·6	15·1	16·5	11·7	25·7	18·3	65–69
70–74	16·7	6·5	12·7	12·2	9·0	14·6	12·3	70–74
75–79	8·9	6·3	8·4	8·0	6·1	6·9	7·3	75–79
80–84	4·5	4·2	5·9	3·8	3·8	4·9	4·5	80–84
85–89	1·2	2·5	2·3	2·4	2·1	2·3	2·1	85–89
90–94	0·2	0·7	1·1	1·2	1·1	1·0	0·8	90–94
95–99	0·1	0·0	0·5	0·7	0·6	0·4	0·3	95–99
100–104		0·1	0·0	0·1	0·4	0·1	0·1	100–104
105–109				0·0	0·0	0·0	0·0	105–109
110–114				0·0	0·0	0·0	0·0	110–114
115–119					0·0	0·0	0·0	115–119
120–124					0·0		0·0	120–124

This table shows the effect of year classes on the mean length of the June shoals.

the bulk of Bear Island cod landed in England. (It should be remembered that although this figure is a mean length distribution of six years' observations, the peak value may fluctuate by as much as 10 to 15 cm according to the entry of good or bad year classes. See Table 2.)

High catches reach a peak in early June and then fall gradually and, at Bear Island itself, the fish becomes patchy and, after July, effort dwindles and is transferred to other areas. Although there are variations in the fishery from year to year, the relative timing of maximum production shows only little change, especially when it is considered that landing statistics are shown by months and that a few days' difference in landing can make a one month's difference to the statistics. Fig. 4 gives the mean catch per unit effort from the Area IIb during the year.

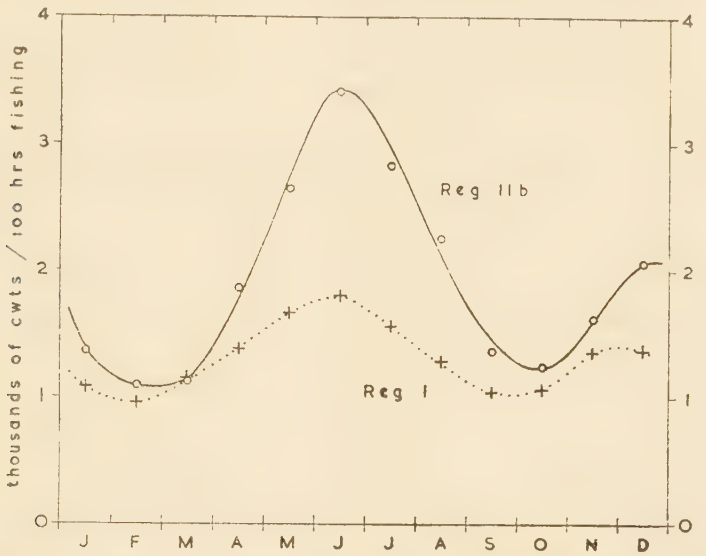

FIG. 4. *Catch per unit effort —per 100 hours fishing—Spitsbergen Shelf (Region IIb): South East Barents Sea (Region I) (Monthly means 1949–1955).*

Although a moderate effort exploits the Spitsbergen and Hope Island grounds in August and September, catches are relatively small. Finally, in the period October to December, catch per unit effort increases again on the West and South Bear Island grounds.

Early in the year, in February and March, there is, in some years only, a low level of effort at Bear Island, based on a demand for codling. At this time much of the fishing is concentrated on the mature cod approaching the Lofoten spawning grounds. Weather conditions at Bear Island are frequently bad in February and March, whilst sea ice may become prevalent on the W. and S. grounds if north-easterly winds prevail for more than a few hours, even into April and May. The ERNEST HOLT has observed a southerly movement of ice of more than 30 miles per day under such conditions and normally only specialist Bear Island skippers fish the area at such times.

ERNEST HOLT CRUISES

LEE (1952) has published the results of the cruises in the immediate vicinity of Bear Island during which bottom temperature and fish distribution were investigated intensively in the years 1949 and 1950. His survey omitted reference to the areas frequented by the cod later in the year—the feeding areas —and his temperature data referred to Bear Island as a geographical area and not to the whole area where cod shoals are fished.

It soon became evident from the July and September cruises in the Hope Island region that those cruises distant from Bear Island would probably be critical from the point of view of understanding the sequence of structure in the otolith.

Methods

During the first few years of the ERNEST HOLT's work a random sample of cod was taken from the pounds each haul for age determination and stomach contents analyses. Originally 10 otoliths were obtained from a haul but later a larger sample of up to 50 were taken from hauls where it was obvious that a major aggregation of cod was being fished. In some cases, for example when the catch was small and fish were scarce on the grounds, the entire catch was utilised.

In the following charts the otolith composition of individual hauls is not shown. Hauls are grouped and the relative size of the total sample is indicated by the size of circle surrounding the area where the group of hauls were made. (Smaller symbol less than 100, larger over 100 otoliths.) In this way the data are smoothed and any sampling errors due to the small size of each haul's sample, are minimised.

FIGS. 5 to 12 (inc.). *Percentage composition and distribution of otolith types from* ERNEST HOLT *samples*

FIG. 5. *April–May* 1949. *Cruise IV.*

April–May

Fig. 5. Cruise IV 1949, April 26th–May 8th on the grounds.

Three areas were sampled during this period. These were:

1. amongst a small group of trawlers fishing in deep water. ± 210 fathoms 60 nautical miles SSW. of Cape Bull. A total of over 1,000 otoliths were collected but for the purpose of otolith type determination this material was subsampled and 353 were identified.
2. The region of the NW. Gully could not be sampled extensively because of floe ice, but three hauls were made and a total of 88 otoliths was examined.
3. During the last three days of the cruise, fishing was carried out in the neighbourhood of a small fleet of trawlers on the North Cape Bank, off the Norwegian Coast. A total sample of 110 otoliths was used for otolith type identification. The shoals in this area included a number of large cod and many sprags from the Lofoten spawning fishery.

FIG. 6. *May* 1950. *Cruise IV.*

April-May

Fig. 6. Cruise IV 1950, April 30th–May 4th on grounds.

This cruise is included because the areas covered differed from those of the previous year and extended the observations to the eastward of Bear Island.

Fishing west and south-west of the Island (Areas 1 and 2) produced only small catches and samples. At the south-east Gullies (Area 3) fishing was also found to be light but

FIG. 7. *June* 1950. *Cruise V.*

further east catches of between 40 and 120 baskets per hour were obtained amongst a small fleet of trawlers (Area 4). A sample of 170 otoliths was used from this area.

June

Fig. 7. Cruise V 1950, May 28th–June 5th on grounds.

Fishing was concentrated on the western edge of the bank between 140–170 fathoms. Heavy catches of up to 200 baskets per hour were obtained. A total of 316 otoliths was used from the three main groups of hauls. No other fishing was reported from the remainder of the Spitsbergen Shelf.

FIG. 8. *July* 1949. *Cruise VI.*

July

Fig. 8. Cruise VI 1949, July 13th–July 26th on grounds.

Sampling began near a trawler concentration on the west side of the South East Gullies (Area 1). Feeding was heavy, with euphausiids as the main species. To the south, west and north-west of the Island (Areas 2, 3 and 4) fishing and feeding were progressively lighter. Those more westerly otoliths had to be judged, as indeed were all previous cruise samples, on the opaque zone of the previous year's growth, for, although the current year's opaque zone was in the process of being laid down, there was insufficient completed to determine what type of zone would result.

Further to the east (Area 5a) good catches were obtained —25 and 120 baskets per hour—from water of temperatures between 0·78°C and 0·98°C. Two hauls from Area 5b gave 200 and 240 baskets per hour from water of 0·20°C to —0·05°C. Most of these otoliths had another opaque zone followed by the beginnings of a hyaline zone on the edge.

Continuing fishing NE. the ERNEST HOLT made two 40-basket per hour hauls (Area 6a) in subzero bottom water of —0·09°C to —0·59°C. Many of these otoliths had begun to lay down opaque material after a narrow hyaline zone—the 'split'—had been completed. The sample contained, however, several large cod with no current year's opaque growth at all. There was thus a wide hyaline zone stretching from the outer edge of the 1948 opaque zone to the edge of the otolith. These fish were mature and from their otoliths were spent virgin spawners. (Rollefsen *ibid.*)

The final area fished was at the edge of the pack ice (6b). Only a small sample fo otoliths was taken from a 15-basket haul. Water was again cold, + 0·23°C.

A total of 654 otoliths was analysed for type.

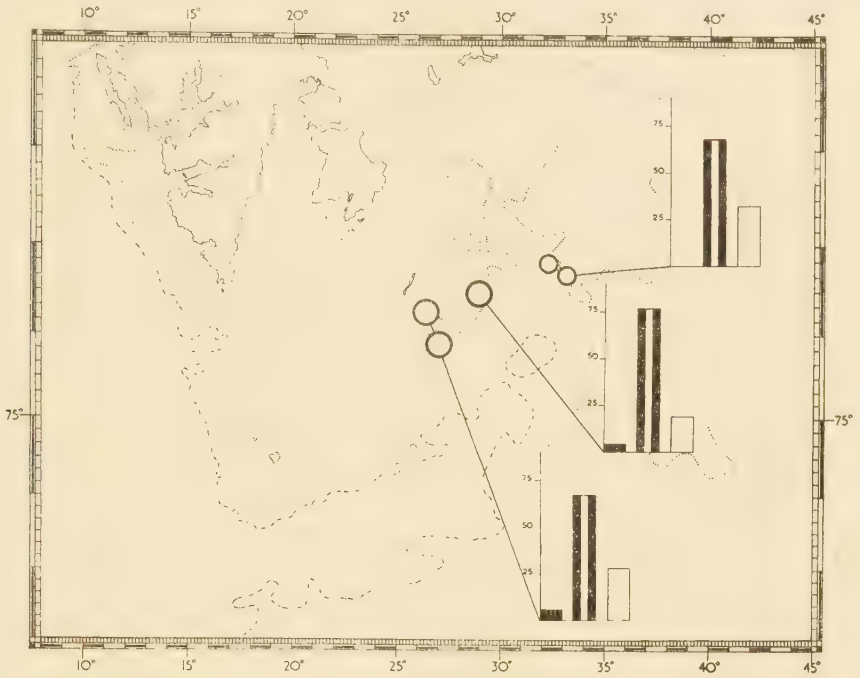

FIG. 9. *September* 1949. *Cruise VII.*

September

Fig. 9. Cruise VII 1949, September 3rd–September 6th on grounds.

This short survey continued the general easterly direction of the previous cruise. Fishing effort was at a low level, in water mostly of between 0·3°C to 0·8°C. A total of 230 otoliths was used.

A small proportion of otoliths of larger fish had insufficient of the current opaque zone laid down for a decision of the type of zone. These had to be judged on their previous year's opaque zone.

A notable feature of this cruise was the substantially higher percentage of the Finmark type of otoliths present in these grouped hauls. The actual number of 'doubtful' types was small.

October

Fig. 10. Cruise VIII 1949, October 11th–October 21st on grounds.

This cruise gave the first opportunity for sampling to the north of Bear Island. Mixed catches of cod and haddock were good on the south side of the Storfjordrenna—up to 40 baskets of each per two-hour hauls—in warm water.

At the north-west Gully somewhat lower catches were encountered with more patchy fishing.

The high percentage of 'split' type otoliths amongst the total sample of 255 was unexpected and was the first evidence against a simple geographical segregation suggested by the previous two cruises.

November

Fig. 11. Cruise IX 1949, November 23rd–November 28th on grounds.

Only small samples, totalling 104 otoliths, were obtained from three grounds on the west side of Bear Island Bank. There appeared to be two distinct shoals; the northernmost,

FIG. 10. *October* 1949. *Cruise VIII.*

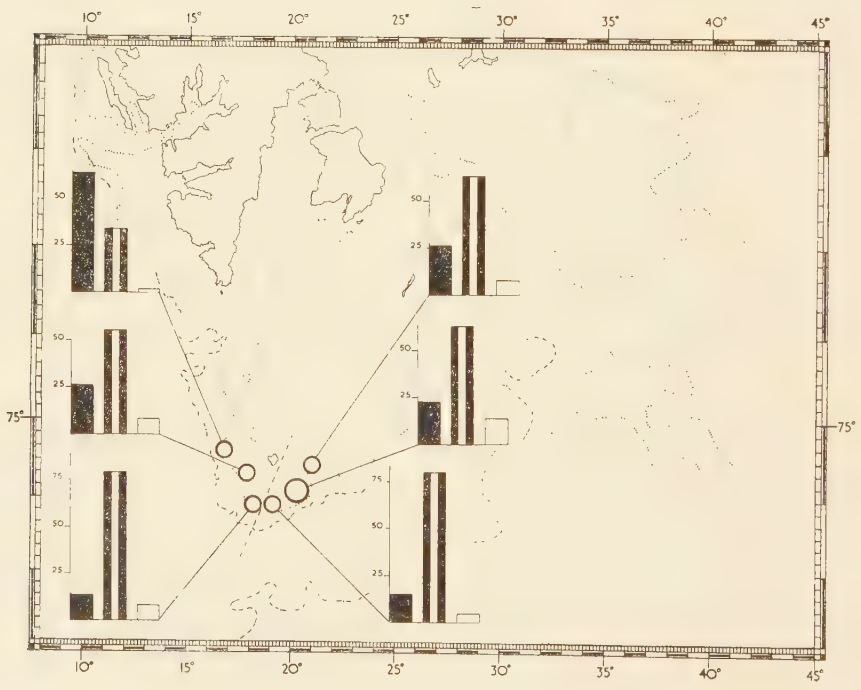

FIG. 11. *Composite chart. November* 1949, *Cruise IX and January* 1950, *Cruise I.*

a deeper and smaller shoal, was found to contain a high proportion of the type 1 otolith, whilst in the remaining shallower samples to the south, 'split' type otoliths predominated.

January

Fig. 11. Cruise I 1950, January 11th–January 20th on grounds.

Grouped trawl hauls for this month are shown on the same chart as the November cruise and show good agreement between the compositions of the two shoals fished in the two months.

The heaviest fishing was south-east of Bear Island but a small sample was obtained further east, at the first head of the South-East Gully. Three groups of hauls are represented for which a total sample of 240 otoliths was analysed.

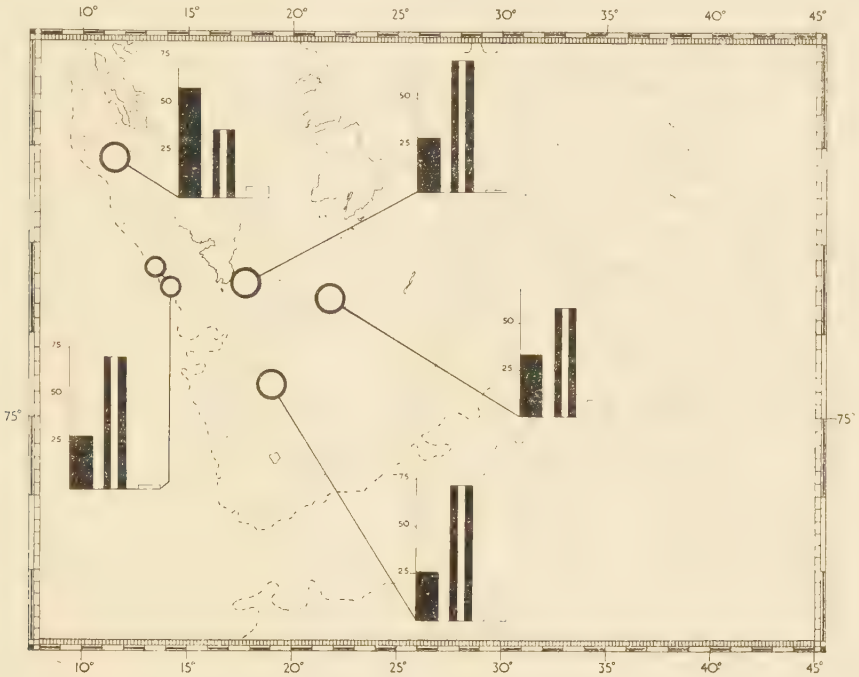

FIG. 12. *August* 1954. *Cruise V.*

August

Fig. 12. Cruise V 1954, August 15th–August 26th on grounds.

This cruise covered widely separated areas not previously sampled at this time of the year —(normally the period of the ERNEST HOLT crew's leave). Fishing was moderate to good in all areas and sampling was distributed between warm and cold water, and was intended to test the cause of formation of the 'split' away from the Hope Island area. A total of 359 otoliths was analysed for type.

Whilst it might have been inferred from the July and September 1949 cruises that there was a geographical segregation of the Bear Island shoals into north-easterly (split) and north-westerly groups, it was obvious from the October cruise that such a simple explanation of the different distribution of the otolith types was untenable. At the same time the presence of the 'split' type from the northern grounds—i.e., the Spitsbergen area —underlined the probability of environment being responsible for the check ring, since the cold E. Spitsbergen current could be expected to provide water of temperature and origin similar to that of the Bear Island Polar current.

An alternative possibility was that there was a circulation of the shoals over the Spitsbergen Shelf and that after leaving the Hope Island area the shoals turned westwards towards Spitsbergen.

THE OTOLITH STRUCTURE

IT IS appropriate now to consider the question of otolith structure and the relationship between opaque zone formations and environmental factors.

Whilst Bückmann (1931) associated good growth and therefore presumably good feeding years in the North Sea plaice with wide opaque zones in the otolith, and the writer observed, in 1950, wide opaque zones being laid down in the Bear Island Cod, a 'warm,' hydrographic year, experimental work by Brown (1946) has suggested that the banding of the otolith is controlled by an innate factor. By keeping brown trout under constant conditions of light, temperature and feeding, she found that opaque material was still laid down at its normal time of year.

Dannevig (1933) rejected the terms 'winter ring' for the hyaline and 'summer ring' for the opaque zones of cod from the Skagerrack, since they are laid down respectively in August to November and November to July (see also Saetersdal 1953). When examined further, however, it would appear from the description of the feeding cycle that even this apparent anomaly conforms. Few details are given, but growth, and therefore it must be presumed, feeding, takes place in the 'autumn'—the cod returning from the fjords to the Skjaergaard the following 'spring'.

In Section V it is shown that the bulk of the older immature cod are found up on the Spitsbergen Bank in June. Previous evidence of the timing of opaque zone formation (1954) showed that most of the cod otoliths began to lay down opaque material towards the end of June or the beginning of July, and ceased by mid-October. This also coincides with the time when higher percentages of fish are found to be feeding and also when the cod is in 100 fathoms or less (see Section IV, Fig. 26), and frequently in cold water.

Now the cod of the Spitsbergen Shelf have, typically, clearly defined and relatively narrow opaque zones which are laid down during maximum growth—whilst the hyaline (winter or 'non-feeding') zones represent the long period November to June when the cod are in deep water.

It will be shown in Fig. 27 (Section IV) that in the SE. Barents Sea the cod spend a longer time in shallow water. Zatsepin and Petrova (*ibid*) working on the food of cod in this area have demonstrated an early start to the feeding period, with a low mid-summer feeding intensity, confined mostly to crustacean food—Euphausiids and also Beröe and similar low value foods. During the rest of the year, except in December/January when feeding is minimal, their diet is largely herring, capelin and young gadoids.

Rollefsen has long identified the otolith type shown in Plate 3, otoliths with wide opaque zones and indistinct and very narrow hyaline zones, with this area where there is a long feeding period. Little is known, however, of the dates of formation of opaque zone in this area.

As this latter area is some 250 miles further south than Bear Island, the latitude difference would allow for earlier penetration of light into the somewhat shallower water and hence, earlier feeding—assuming comparable turbidity. Since the North Cape current is also of Atlantic origin this is a reasonable assumption.

As (a) the period of feeding, (b) the time spent in the shallow water and (c) the period during which opaque material is laid down in the Spitsbergen Shelf area, are all equally displaced in relation to the incident light curve, there is therefore evidence from the field that opaque zone formation is related to feeding, and not to light. Dr. A. Dannevig's apparent anomaly would also help to confirm this. Water temperature is also ruled out because the cod can at times enter sub-zero water where it feeds heavily and it seems that after the initial shock—when a check ring is formed—normal opaque material continues to be laid down. No evidence is available to delimit the level of feeding required to cause the change from hyaline to opaque material or whether other factors assist in the formation of the latter.

It has been shown (1954) that growth of the otolith and the fish continues during the 'non-feeding' period—which implies a certain measure of feeding—but growth is at a considerably lower rate; this is seen from the relative width and length of period in which the two zones are laid down. On the other hand, the hyaline zone occurring mid-way during the formation of the 'split' type opaque zone does not represent a non-feeding period. Its time of formation is of the order of two to three weeks during the height of the feeding season and is associated with the entry of the cod into cold water—water approaching or below 0 C. Molander (1947) has reported a check in growth and a hyaline check ring in

plaice otoliths when the temperature of their aquarium was allowed to fall. Similar shocks, e.g., marking, have previously been observed by several workers to be followed by a check ring appearing in scales or otoliths (Buchanan-Wollaston 1933).

There is, finally, the question of degree of darkness of the opaque material in an otolith. The immediate history of feeding of any given group of cod can only be assumed. Normally on reaching the Bear Island Bank cod begin to feed on euphausiids (see Section V, Fig. 30). This persists for most of the time on the western edge of the banks as far north as Spitsbergen, and a low level of fish food has been observed, including herring, at the end of the feeding season. On the other hand, cod reaching the Bank south of the Island begin to feed on euphausiids but as they progress NE., change to the capelin. There is some evidence that this change of food organism is associated with a change in density of the opaque material, it being darker in the second phase when the cod is feeding on fish.

On the other hand, from the Russian work already mentioned (Zatsepin & Petrova 1939), fish form the principal food of the SE. Barents Sea cod shoals. Whilst the amount of opaque material in their whole otolith is greater than in otoliths from cod of the Spitsbergen Bank, there would not appear to be an obvious difference in relative darkness, i.e., thickness or spacing of the lamellae. Again, according to them, euphausiids are taken only in mid summer when there is a temporary scarcity of young fish and before feeding on young haddock and cod begins. During this period any organism present may be taken, but, in the SE. Barents Sea otolith samples so far examined, no striking differences in density are apparent.

It was decided to test by means of tagging experiments the simple hypothesis, 'that the Bear Island shoals separate at Bear Island and proceed in two groups, one north eastwards to Hope Island and beyond, and the other northwards to Spitsbergen.' These are described in the next section.

SECTION III

TAGGING EXPERIMENTS OF 1951 AND 1952

The 1951 Releases

The areas chosen for this experiment were the Hope Island Bank in late August and the South, SW., and West and NW. Coastal Banks of Spitsbergen. It was thought that these grounds might be found to be representative of the differing habitats encountered by each of the two populations.

Hope Island

Tagging and liberation took place at Hope Island between the 23rd and 28th August 1951, inclusive.

As the intention was to release as many as possible from one position and a suitable number of the cod was obtained from the head of the Gully south-east of Cape Thor, in from 80 to 110 fms, a dahn was dropped and fishing continued at a steady low level of catch until a total of nearly 2,000 had been released. An average of approximately 75 cod were tagged and released per haul with the vessel stationary after each haul. Weather was exceedingly good and the area of release was covered by a circle of 5 mile radius from the dahn buoy.

The tags used were of two kinds—the orthodox numbered Petersen opercular button of black ebonite attached by a silver wire through the operculum to a blank black button (998 total) which were being tested against the Norwegian Hydrostatic Tag, (997 total) made by Dr. Einar Lea. The latter was attached to the back musculature immediately in front of the first dorsal fin, by means of a 'one ended' stainless steel bridle. (Plate 5.)

The cod were in excellent condition, well fed, firm and very lively. They were on the whole good 'sprag' with the main modes at 80/84 cm, and smaller codling at 40/44 cm; the latter represented the good 1948 year class. (See Fig. 13.)

Three trawlers only passed near the ERNEST HOLT, during her fishing

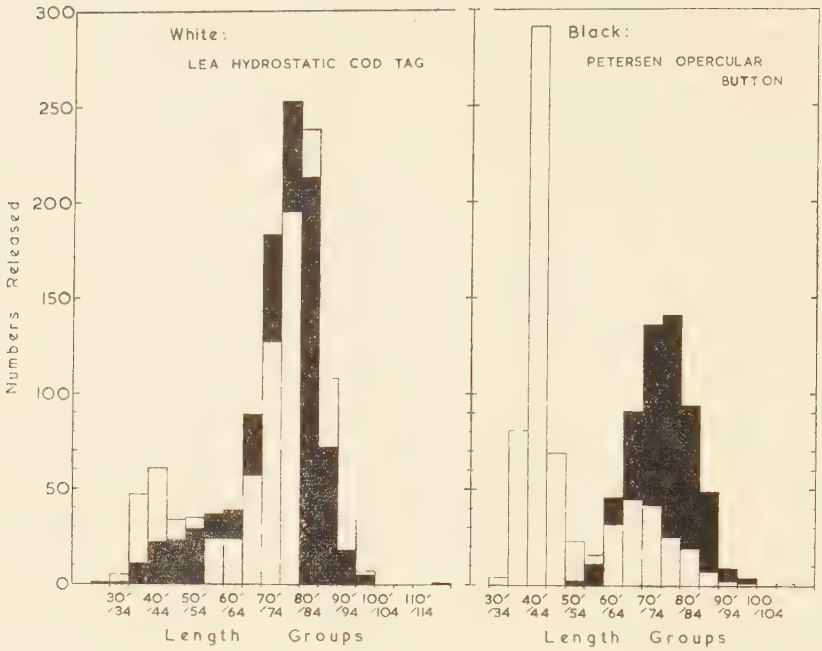

FIG. 13
Length composition of tagged cod released at Hope Island, August 1951.

FIG. 14
Length composition of tagged cod released at Spitsbergen, September 1951.

Spitsbergen

At Spitsbergen, fishing was light along the entire West Coast with a predominance of the 40/44 cm codling and 400 below 50 cm were tagged between September 6th and 12th off Hornsund. Almost all those cod whose lengths fell between 65 and 80 cm were caught on the Sorkapp grounds. Weather frustrated the aim to release a further 2,000 and only 1,241 could be tagged—583 Petersen and 658 Lea. Furthermore, whereas at Hope Island the length distributions for each type of tag were roughly comparable, at Spitsbergen no opercular tags were used on fish below 50 cm, as it was thought that the opercular technique was too brutal for such small fish, whilst the bulk of the Lea tags, over 500, were used on codling below 60 cm. Their length distributions are shown in Fig. 14. The recapture frequencies of the two release groups, Hope Island and Spitsbergen, are therefore not directly comparable except as percentages of each length group released.

No trawlers were seen at Spitsbergen nor, it was learned, were any fishing in the vicinity.

Results from First 30 Days

Hope Island. Fishing effort remained very low in this neighbourhood and only six returns were made within this period, i.e., until the end of September. Their recapture positions given indicate that all but one had moved northwards, four in fact, had moved NE. (see Fig. 15).

Spitsbergen. Here again fishing effort was low and only five returns occurred before the end of September 1951. Four had moved north-west and one was only a few miles from its release position. No returns were obtained from the more northerly releases.

Returns in First Twelve Months

Fishing remained light around Bear Island and no other recaptures were made on the Spitsbergen Shelf until April, but between late April and mid-July, 28 returns were made

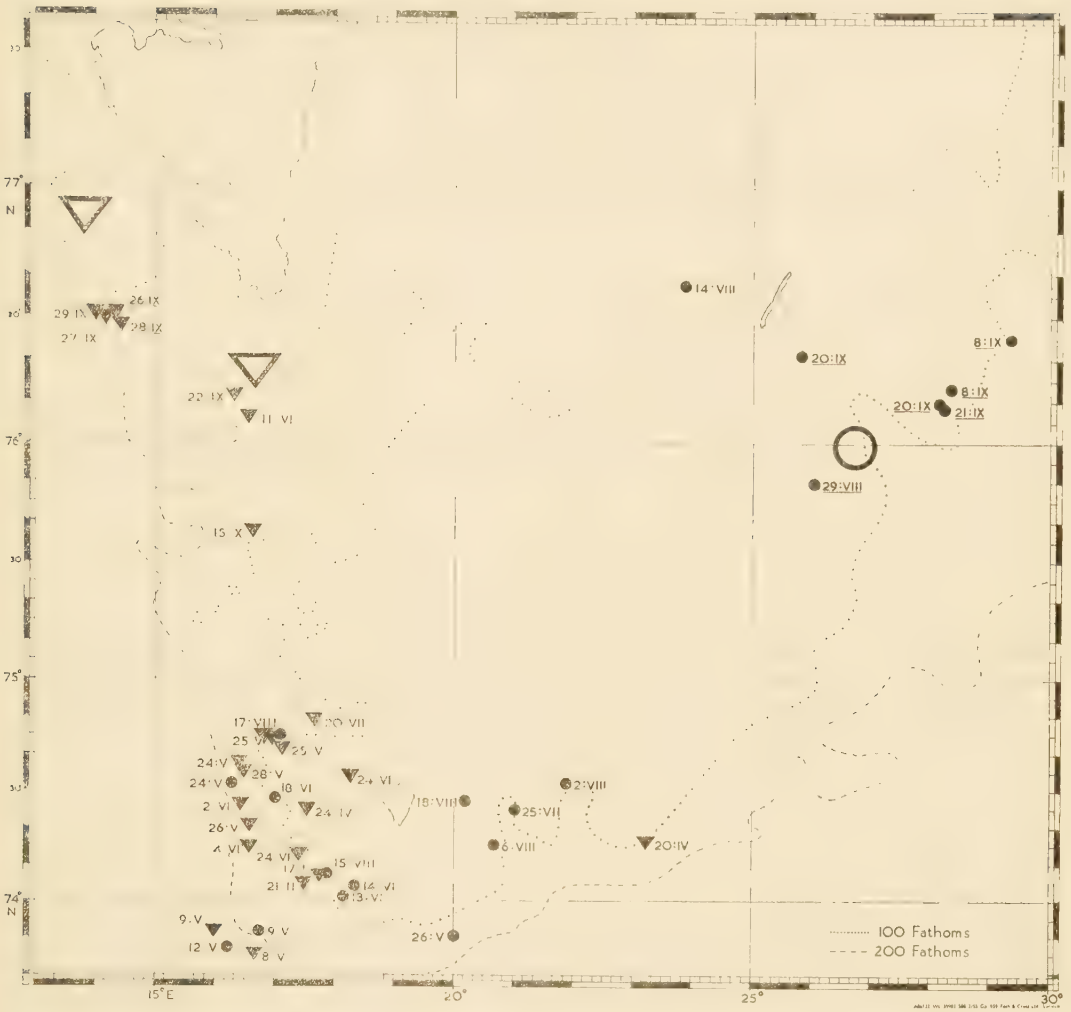

FIG. 15. 1951 *Experiment. Total known recapture positions on Spitsbergen Shelf in first 12 months.*

Underlined dates are of the calendar year of tagging, i.e. 1951.

from the Bear Island Bank, from the NW. Gully to the east of the SE. Gullies, whilst within the next month, as the fishing moved further north-east and north-west, a small number of recaptures were made at Hope Island and Spitsbergen. Fishing effort was, however, particularly light in these two areas during 1952. These recaptures, which were made in late August and September fall strictly speaking within the second year.

Fig. 15 gives each position of recapture during the first year, followed by the date, whilst Fig. 16 is a summary of all recaptures on the Spitsbergen Bank to the end of 1956. In all, some 40 returns, derived from the 1951 Hope Island and Spitsbergen release areas, were made within a 60 mile radius of Bear Island, thus supporting the hypothesis that the Bear Island shoals are composed of mixed populations, which later spread and feed in different areas, but return to Bear Island in the winter months.

SECOND TAGGING EXPERIMENT, 1952

In 1952 a second tagging cruise was undertaken, this time in June, in order to attempt to trace in detail, the separation of the shoals from the Bear Island Grounds.

FIG. 16. 1951 *Experiment. Total recaptures on Spitsbergen Shelf to end of* 1956.
Triangles = Spitsbergen releases; circles = Hope Island releases.

Tagging took place in three main areas on the Bear Island Bank:

1. South of the NW. Gully
2. South-south-west of Cape Bull
3. South-east of Cape Bull

It was not possible to obtain Lea tags in time for this cruise and yellow Petersen buttons, alternate 100s. having message tags of polythene attached, were used instead. The messages were flat and the texts readily legible without removing the tag from the fish. No differentiation will be made in this paper between returns bearing the different types of tag.

Area 1. Fish suitable for tagging were obtained with difficulty from the first area chosen, just south of the NW. Gully, since the fish were in a very low physiological condition; thin, with concave belly line and contrasting markedly with the vigour of the well-fed cod tagged both at Hope Island and at Spitsbergen the previous year. Here in June the water was warmer—mostly between 2° and 4·5°C. The rejection rate in the tanks was very high—frequently above 75 per cent each haul. Eventually 1166 cod, mostly of small size, 50/55 cm (Fig. 17) were released between 6th and 9th June inclusive.

Area 2. At area 2, in cooler water 1·6° to 2·7°C, 1579 cod of slightly larger size (Fig. 18) were tagged and released. Fish here were in somewhat better condition. In both these areas tagging was carried out amongst a fleet of English and Russian trawlers which varied in number between 20 and 30 ships. Consequently many cod were caught after they had been at liberty for only a few days.

Area 3. In the third release area, no commercial fishing was taking place and the last release of 1375 cod and codling was from shoals of very different size composition. These shoals were comprised, on the whole, of actively feeding large fish and included some spents. (Fig. 19.) Returns show that within the first 30 days a total of 70 fish were reported or returned, made up as follows, 48, 20 and 2 from Areas 1, 2 and 3 respectively.

The number of cod recaptured from the whole shelf irrespective of release area fell away rapidly after the end of June as follows, July—7, August—10, September—7, October —Nil, November—1, December—12.

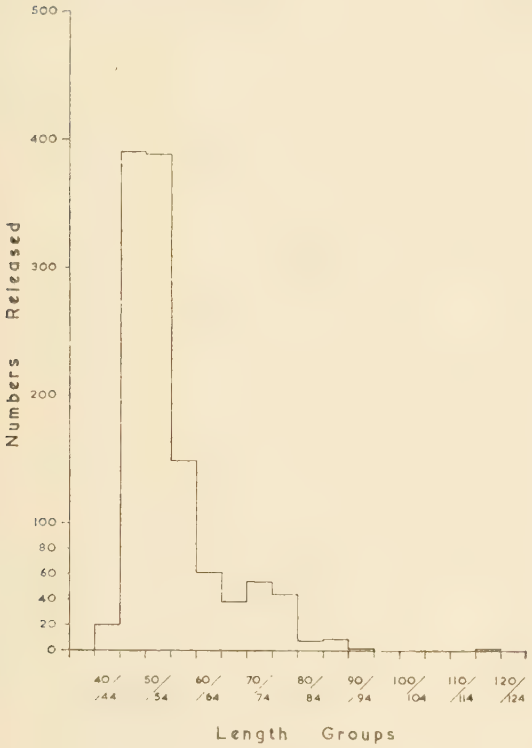

FIG. 17. *Length composition of tagged cod released at North West Gully, Bear Island, Area* 1, *June* 1952.

FIG. 18. *Length composition of tagged cod released SSW. of Bear Island, Area* 2, *June* 1952.

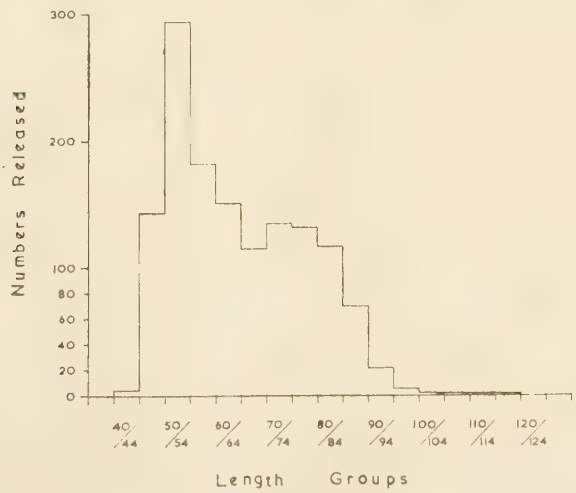

FIG. 19. *Length composition of tagged cod released SSE. of Bear Island, Area* 3, *June* 1952.

It was unfortunate that, during 1952, fishing effort was only some 60 per cent. of 1951, and little fishing took place on the Shelf until winter.

The twelve cod tags returned during the month of December came from south or south-west of Bear Island. Fig. 20 gives the distribution of all returns for which positions

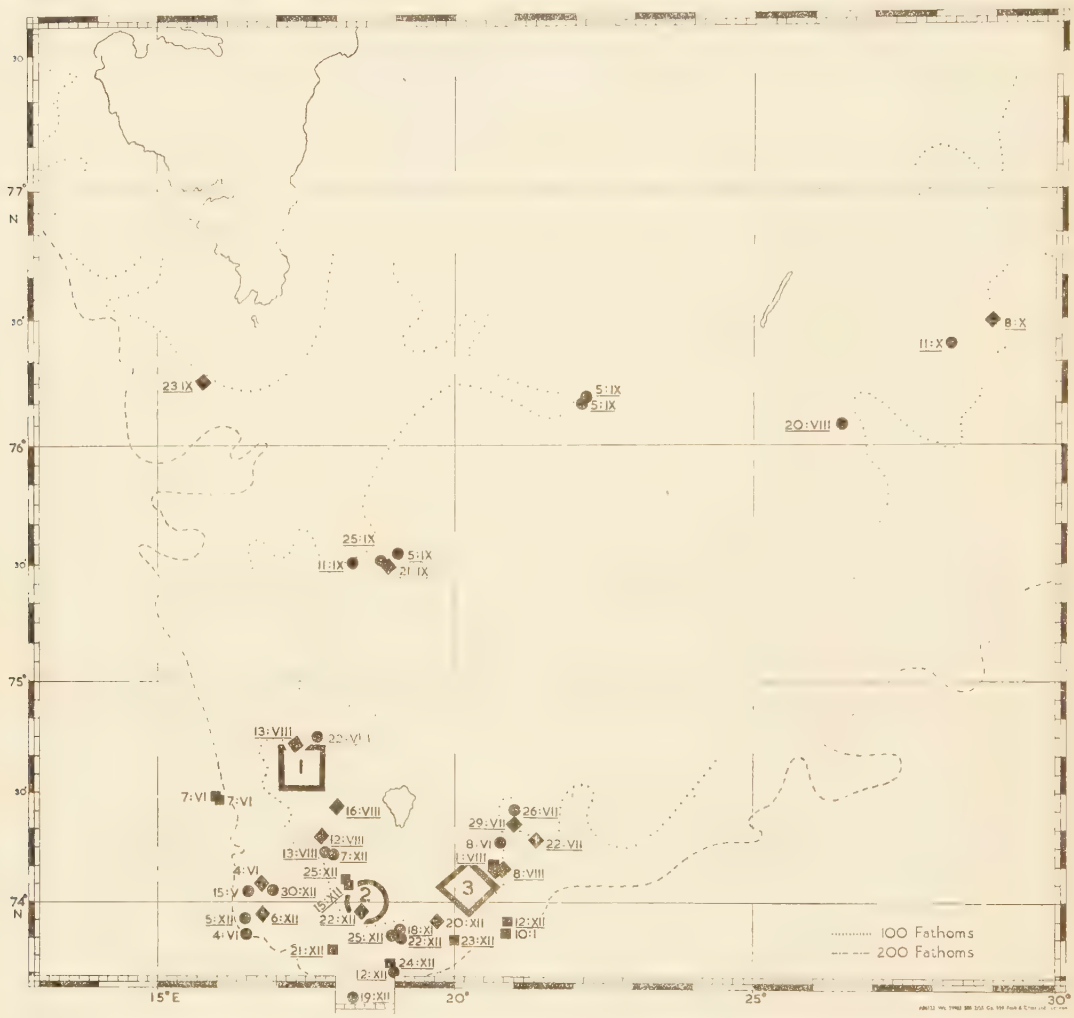

FIG. 20. 1952. *Experiment. Total known recapture positions on Spitsbergen Shelf in the first* 12 *months.*

Underlined dates are of the calendar year of tagging, i.e. 1952. (Recaptures in first 30 days excluded.)

were available for the first 12 months from the Spitsbergen Shelf alone, i.e., during the period June 1952 to June 1953 excluding the first 30 days. Underlined dates refer to the year 1952—the rest to 1953.

It is of interest to note that only few recaptures from 1952 Area 1 were made and these were restricted to the winter months, or even the following year, i.e., after their winter return to the general area of Bear Island.

It may, however, be deduced from the data above that cod of the S. Bear Island Bank spread from the June shoals of 1952 and reached both Spitsbergen and Hope Island during the fishing season, no matter from which area of the Bear Island Bank they had originally been released. Detailed migration routes from the immediate vicinity of Bear Island could not be elucidated as was hoped, because of the low effort and restricted areas of fishing.

Since the fishing effort remained low during 1953 and 1954 and only few recaptures were made on the Spitsbergen Bank, the results of the two experiments, 1951 and 1952,

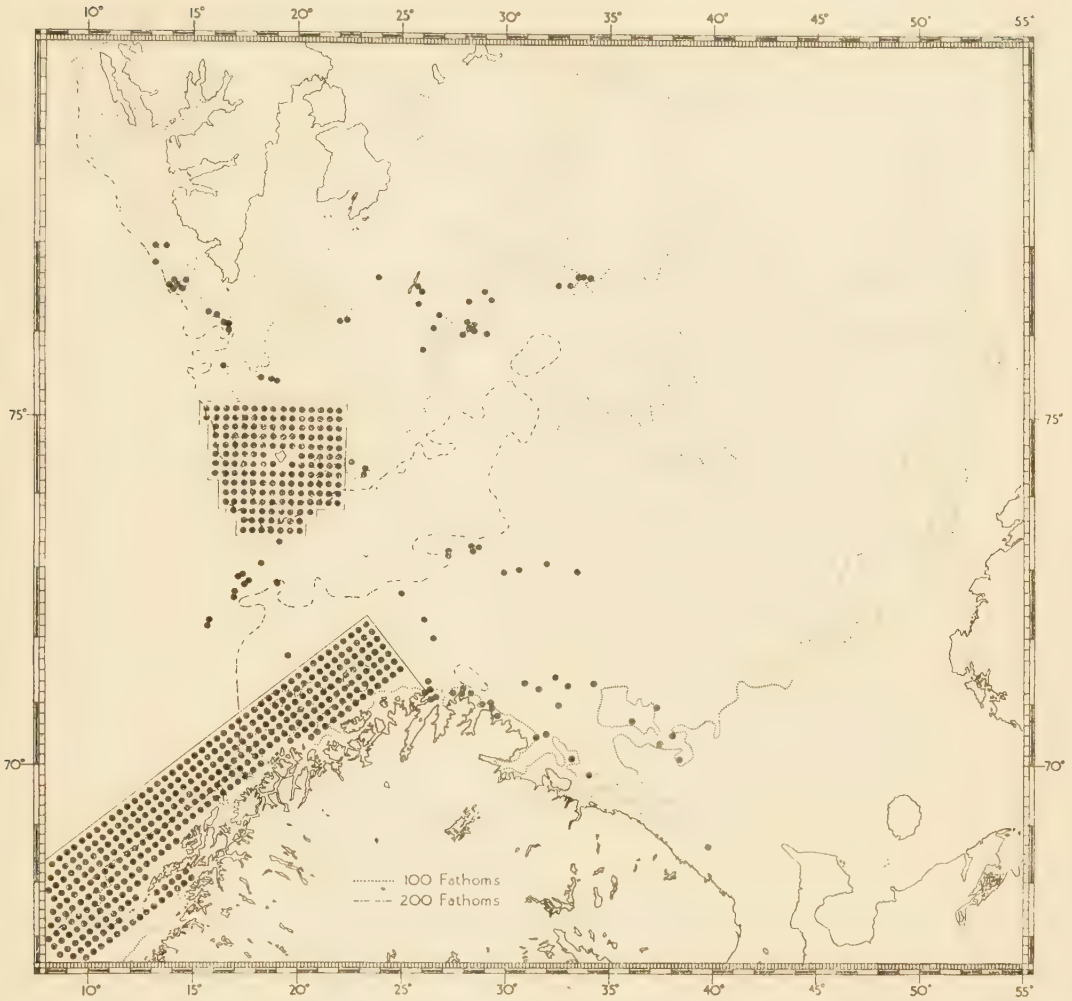

FIG. 21. *Total known recapture positions from* 1951 *and* 1952 *experiments to the end of* 1956.

Bear Island and Norwegian Coast recaptures west of North Cape, are shown diagrammatically—172 and 349 respectively.

are summed and included in Fig. 21 irrespective of area or date of release. Their length composition is given in Fig. 22.

RESULTS OF BOTH EXPERIMENTS

Returns away from the Spitsbergen Shelf.

So far only recaptures on the banks—the main 'summer/autumn' habitat of the Bear Island cod—have been dealt with. It is proposed now to deal with returns from outside this area. They fall into three main categories:

I. The spawning area of the NW. Norwegian Coast from North Cape, southwards through the Lofotens to the older spawning ground of Romsdal.

II. The SE. Barents Sea Banks and their approach routes, i.e., including the E. Finmark Coast and coastal banks, and finally

III. The so-called 'Wintering Grounds' south of Bear Island (Maslov, 1942)—the area where the immature fish are thought to reach the southern limit of their winter migration and through which mature fish on passage to the spawning grounds must also pass.

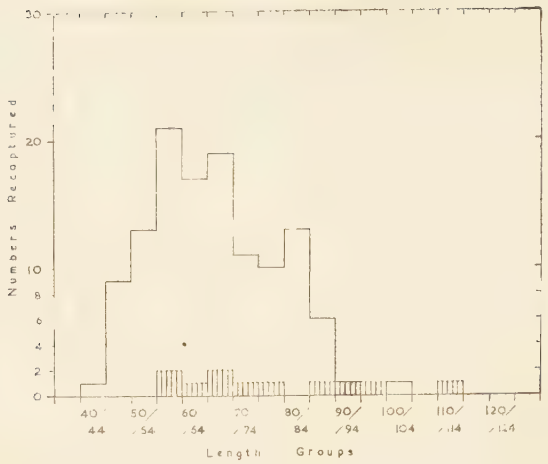

FIG. 22. *Length composition of Spitsbergen Shelf recaptures, where available, 1951 and 1952 experiments.*

Vertical hatching shows "wintering ground" recaptures.

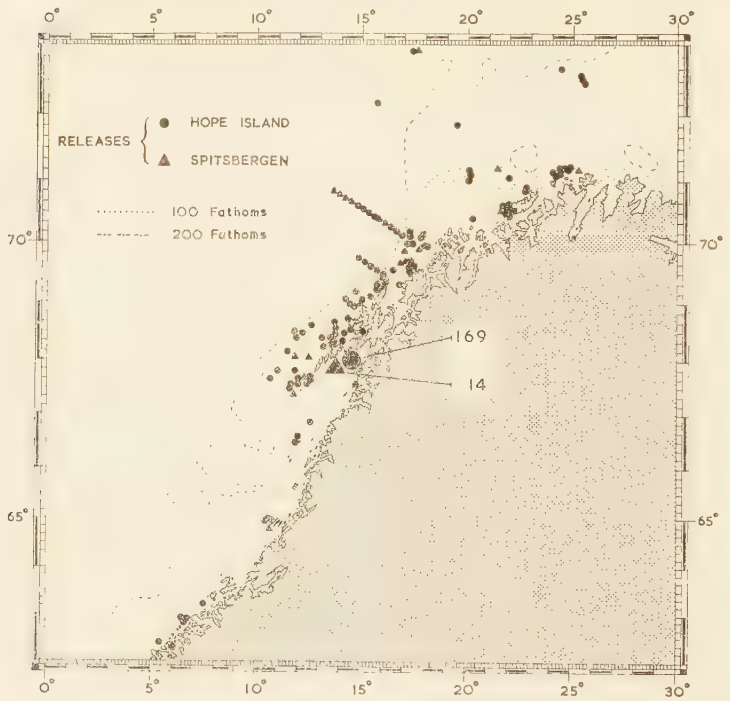

FIG. 23. 1951 *Experiment. Recapture positions on Norwegian Coast and outer banks.*

Vestfjord recaptures shown as totals.

I. *Spawning grounds—Norwegian Coast*

Figs. 23 and 24 show the recapture positions of fish caught on the outer banks during the first spawning season after tagging. It will be seen that some recaptures extend as far south as the latitude of Romsdal and in depth out to the 200 fm contour and just beyond in the latitude of the Lofoten Islands. The total for 1951 and 1952 experiments recaptured on the Norwegian Coast are shown grouped in Fig. 21 since the large number of individual recaptures cannot be shown with accuracy in the narrow fjords and sounds amongst the islands, which make up the densest spawning regions.

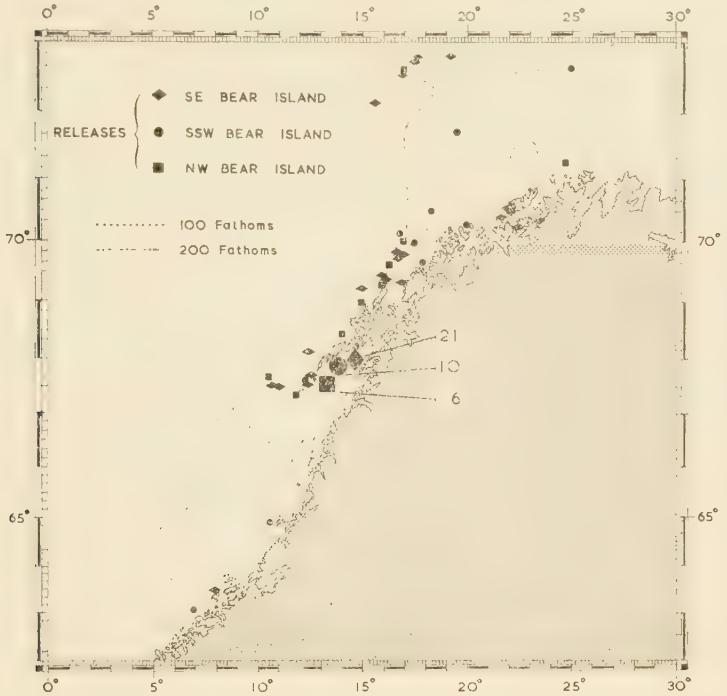

FIG. 24. 1952 *Experiment. Recapture positions on Norwegian Coast and outer banks.*

Vestfjord recaptures shown as totals.

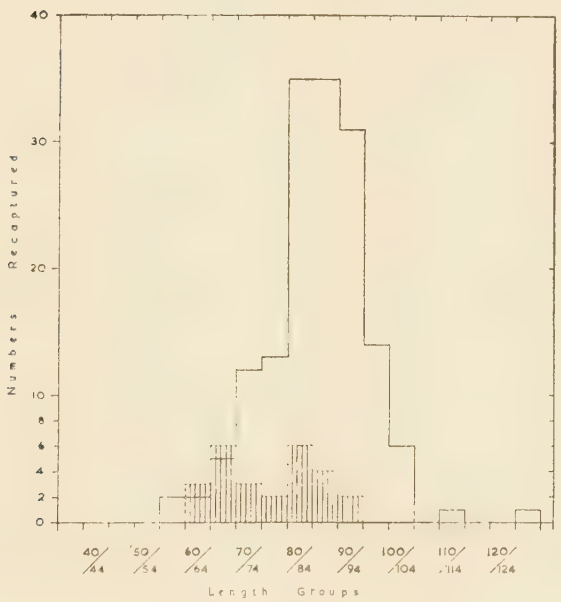

FIG. 25. *Length composition of Norwegian Coast recaptures, where available,* 1951 *and* 1952 *experiments.*

Vertical hatching shows lengths of South East Barents Sea recaptures.

The length composition of these mature recaptures is given in Fig. 25 for the 1951 and 1952 experiments, where known.

II. *SE. Barents Sea*

It will be seen from Fig. 21 that tag returns from commercial fishing can be divided roughly into two areas of the Barents Sea by the Bear Island Channel and the Hope Island Deep, the greatest density of recaptures corresponding to the most frequented banks. Eastwards of North Cape, south of latitude 74 N, there is a total of some 33 returns and a further 5 with approximate areas of recapture only —e.g., E. Finmark Banks. The length composition of this SE. Barents Sea group is given in Fig. 25—vertical hatching.

III. '*Wintering Grounds*'

South of Bear Island a small group of returns from deep water—all from more than 200 fathoms (≏ 365 metres) were caught between the months of February and May and derived from both tagging experiments, irrespective of release position. Their length composition shows them to be mixed immature and mature. (Fig. 22.)

Summary of Results

From these charts it is evident that cod of the Spitsbergen Sh elf, in the course of time—a small number of years—penetrate to all regions of the Barents Sea, fished by commercial vessels. There appears to be a pattern of circulation and it is of interest to see that in the matures, too, there is an easterly trend in their spread, after spawning, which parallels the observations made from the immature otoliths and the tagging results on the Spitsbergen Shelf.

SECTION IV
VERTICAL MOVEMENT AND ANNUAL DEPTH CHANGE

In the literature of fish migration there are many references to a summer inshore migration —usually assumed to be 'for feeding'—and a winter movement away from the coast—often associated with, and in many cases assumed to be dependent upon, a seasonal fall in temperature.

Meek, however, (1916) refers to a pattern of movement of the North Sea cod, the behaviour of which is, apparently, reversed. He refers to an increase of cod in deeper water in summer —"They return in autumn (to moderate depths) and remain inshore until early summer, when they move into deeper water . . ."

In more recent years, Steven (1948) described the wintering of mackerel on the bottom in deep water of the Hurd Deep area and its summer movement into shoaler depths where it is more usually associated with a pelagic fishery. He also points to a confusion which has arisen in the literature when a shoreward migration also coincides with a movement towards deeper water, as for example when the deep lies near the coast.

Tåning (1952) and Devold (1952 and 1955) have also given the depths at which herring occur in the Faroes area and the Greenland Sea respectively at different times of the year.

Hickling's quarterly charts of hake distribution (1927) show their summer entry into shallower water. This was also described by Hart (1948) but as a shoreward migration. McKenzie (1934 and 1956) related midsummer peak cod landings in Nova Scotia to this movement into shoaler water in summer and gave the figure of a 50 per cent change in depth between winter and summer.

There are, however, as far as the writer is aware, no instances of data of changes in depth being available for all periods of the year for a given species and very few quantitative data appear in the literature.

PLATE 1. *Opaque zones of Type* 1, *Western type, are seen in the four outermost zones.*

PLATE 2. *Opaque zones of Type* 2, *Split type, are seen in the four outermost zones.*

PLATE 3. *Opaque zones of Type 3, Eastern or Finmark type, present throughout the otolith.*

PLATE 4. *Otolith showing sequence of Western, Split and Eastern opaque zones.*
Otolith from tagged cod recaptured in South East Barents Sea.

PLATE 5. *The Lea Hydrostatic cod tag, attached in front of first dorsal fin by means of single ended stainless steel bridle.*
(Tag has been compressed by water pressure.)

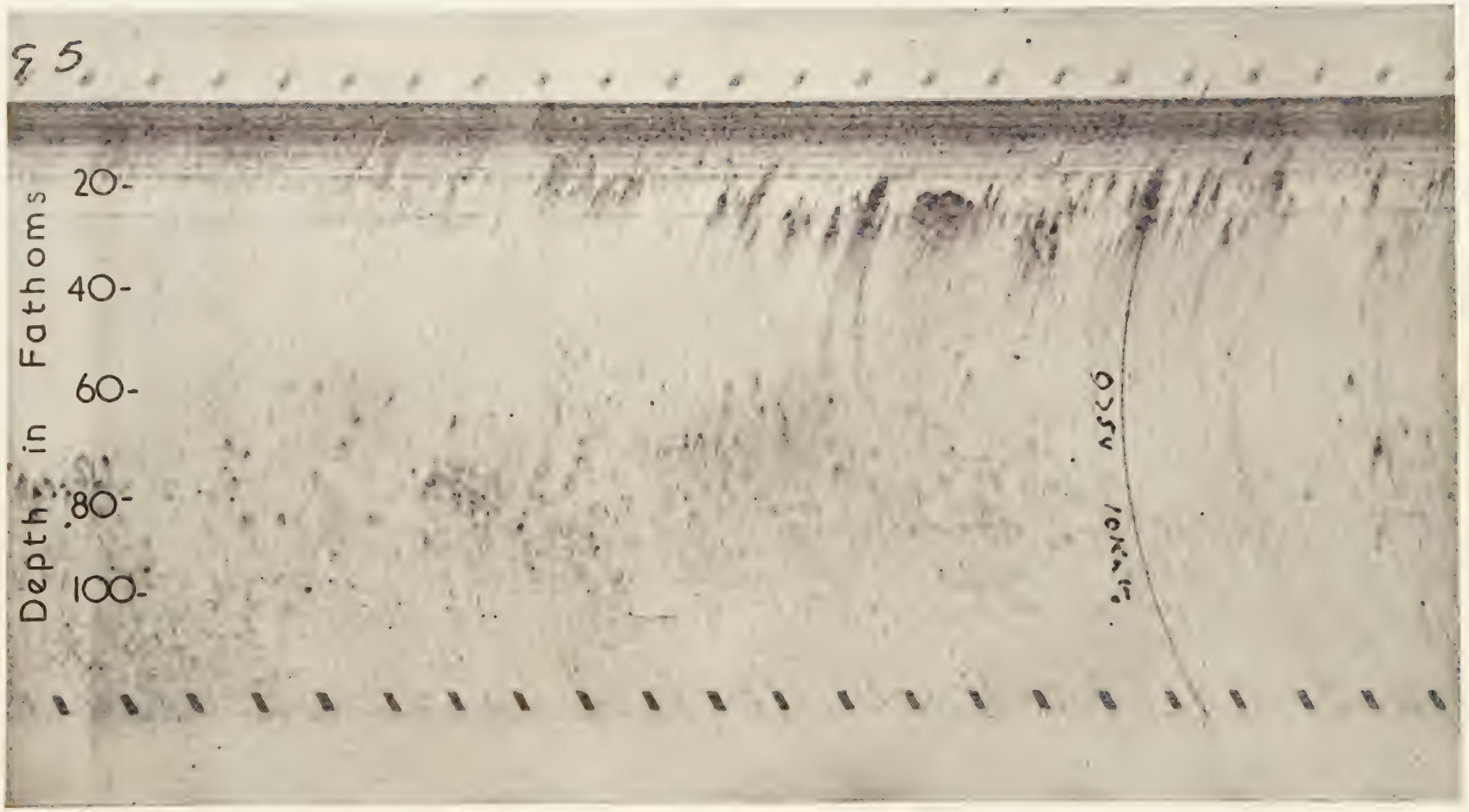

PLATE 6.

10 K.C. *Echo sounder trace showing two layer echoes—upper trace probably capelin shoals; lower trace, cod, appearing individually as 'comets'*

To the fishing skipper in the Barents Sea, adherence to a given depth has long been the method of remaining on fish, i.e., at a particular time a particular depth is more rewarding than those deeper or shoaler.

Whenever the ERNEST HOLT has fished in the Barents Sea details of her fishing have been passed to commercial vessels by W/T and R/T. Several vessels exchange information each day and frequently include catch and depth in their reports; how much feeding was observed and what were the most important organisms of food, were also given, even though the exact position was frequently, quite naturally, omitted. These W/T and R/T reports so obtained have been analysed for the years 1949–1955 inclusive, and also for the first part of 1956.

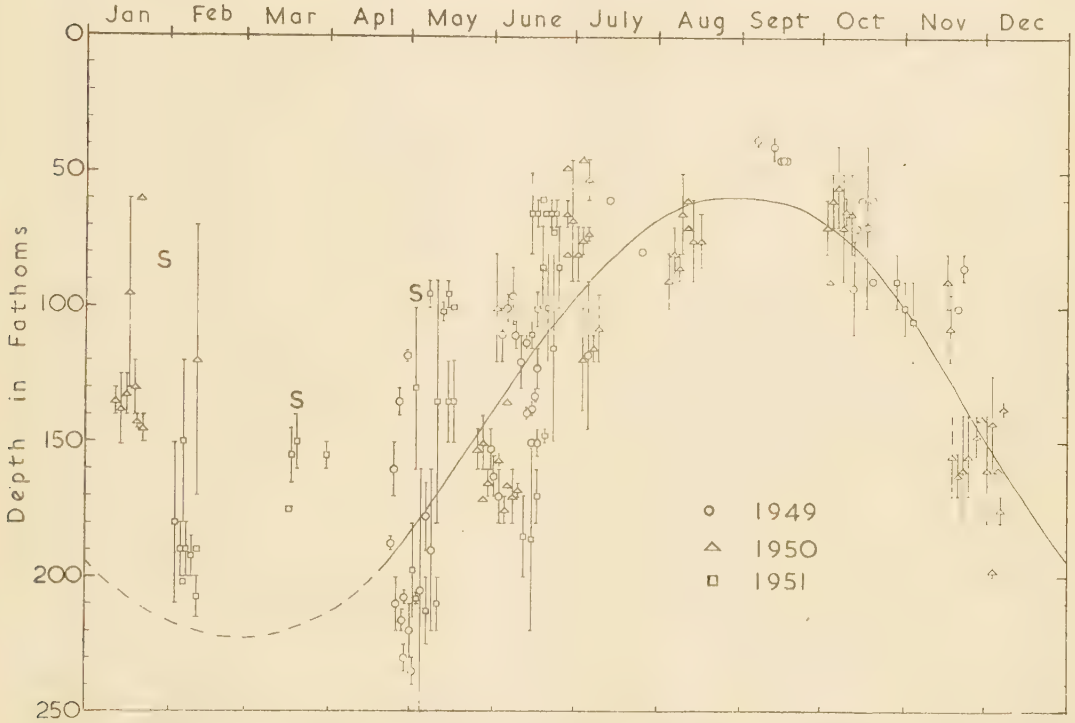

FIG. 26. *Mean annual depth curve of cod, Spitsbergen Shelf, west of 21°E., from commercial trawler W/T reports received by* ERNEST HOLT, 1949–1951.

SPITSBERGEN SHELF

Fig. 26 is based upon these wireless reports from the Spitsbergen Bank, both east and west sides, for the first three years of the HOLT's work, 1949–51. The curve is assumed to indicate the depth of maximum fishable concentration of the cod. Where reference has been made in the W/T reports to other species, notably haddock, the data have been omitted in case that species determined the choice of ground. Other species, on the whole, occur too sparsely to affect the choice of a trawling ground in this area of the Spitsbergen Bank. On the other hand, size of fish varies with depth and it must also be assumed that trawlers will aggregate on to shoals of larger rather than smaller cod, in the normal course of fishing, except when there is a demand for codling, as already mentioned, in the months of February and March. Furthermore, the presence of 'category small' on the grounds was usually lamented in the W/T reports. These are annotated, "S", in Fig. 26. It is reasonable to assume, therefore, that the curve of depth-change reflects the mean annual vertical movement of the bulk of the population of older but still predominantly immature fish. The curve was drawn through the observations by eye, whilst the broken line is an extrapolation based upon the hypotheses, that the immatures winter deep in the West Spitsbergen Current and are not fished

systematically each year by the trawlers. This is discussed more fully in Section VI. A further reason for not drawing the curve through the observations obtained in January, February and March was that in each case the commercial fishing reports have always stressed the small size of the fish from the shallower parts of the bank fished. These observations did not, therefore, refer to the major part of the population, to which the rest of the curve applies.

The counter attraction of the Norwegian Coast fishery, at Malangen's Ground and Andanaes, for large mature and pre-spawning cod, usually means that apart from the few ships seeking codling on the Bear Island Bank, the main part of the immature stock is little-fished during the months of February and March and sometimes April, when they are at depths of the order of 200–240 fathoms.

In June 1949 the ERNEST HOLT's echo sounder picked up cod shoals, west of Bear Island, well off the bottom where the water was deep (Plate 6) but touching the shelf at their eastern shallower boundary. This has been a frequent observation since. Saetersdal (1955 and 1956) has also shown pelagic shoals to be in SE. Barents Sea, whilst Ellis's (1956) observation also demonstrated a diurnal vertical migration of limited extent in the Skolpen Bank region, during a 24 hour fishing period. During his observations, fishing was carried out between two dahn buoys, and despite the fact that traces, assumed to be cod, were visible off the bottom on the sounder records, reasonable catches of between 70 and 35 baskets per haul were maintained. Much of the cod population, therefore, is probably pelagic.

It must be realised, therefore, that this annual depth curve gives only a relative picture of the depth at which trawling was carried out and not necessarily the actual depth of the cod population during the year. It is not known what proportion of the local population is present pelagically. Nor has the relationship between the pelagic cod and the bottom cod been investigated, but during the feeding period they are thought to be actively-feeding and quiescent-digesting phases respectively.

South East Barents Sea

Depth information from W/T material, for the SE. Barents Sea grounds, outside the area normally worked by the ERNEST HOLT, is only scanty. Through the kindness of Mr. Tom Boyd, records of voyages made by the entire fleet of Lord Line Trawlers Ltd., of Hull, for the year 1954 have been made available. These data have been added to W/T information and are reproduced in Fig. 27.

Whilst the basic patterns of the curves from the two major areas of the Barents Sea are similar, there are differences in timing and amplitude of the movement which reflect the different topography of the two areas. There is a comparable winter period during which the fish are deep and a summer period when they are in shallow water, but the spread in depth during the early months of the year is thought to be related to the fishing of shoals of mature cod, aggregating over a wide area of differing depths as they approach the Norwegian Coast on their spawning migration.

More data are required for the SE. Barents Sea, however, before the depth curve shown in Fig. 27 can be considered as representative as that for the Spitsbergen Bank.

It should be pointed out that the dates of the HOLT's cruises on these grounds varied in successive years, so that her collection of W/T reports was intermittent. However, it is thought that major variations in the depth of trawling could not have taken place without knowledge. The fact that the mean curve of the succeeding four years, 1952–1955, compares closely with Fig. 26, supports this view.

Marked Fish

There are sufficient data from recaptured cod, released in the two experiments described earlier, which include observations on the depth at which the marked fish were recaptured, to allow a check to be made on the behaviour of the marked population. Fig. 28 shows the total depth data of recaptured cod. No recapture data of those returned from the SE. Barents Sea are included. This figure relates entirely, therefore, to Spitsbergen Shelf (solid symbols) and Norwegian Coast (open symbols) recaptures. Although these data are not

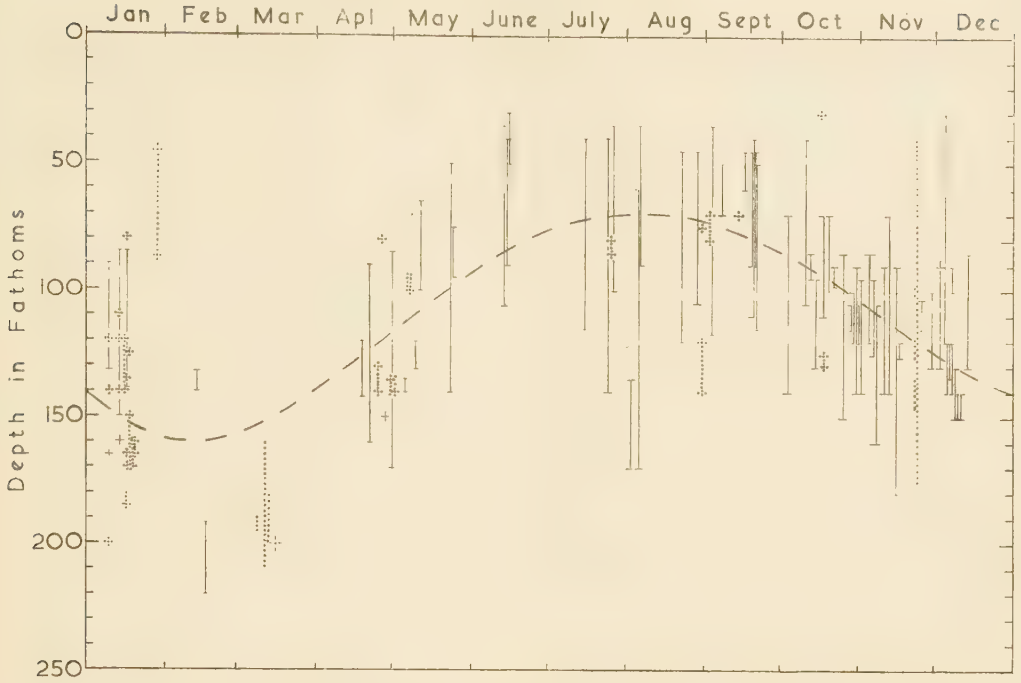

FIG. 27. *Mean annual depth curve of cod, of SE. Barents Sea, i.e., East of North Cape.*
Solid lines, data for 1954 kindly supplied by Mr. Tom Boyd, Lord Line Ltd., Hull — remainder from W/T reports.

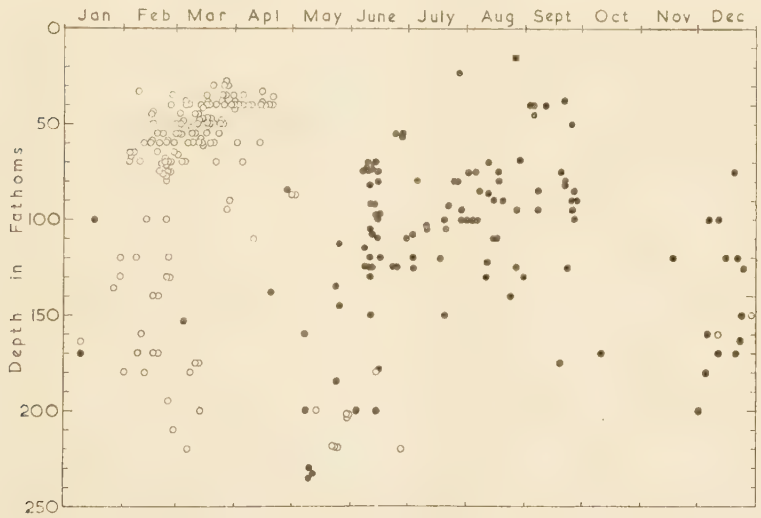

FIG. 28. *Depth distribution of recaptured cod, where known, from* 1951 *and* 1952 *experiments.*
Norwegian coast recaptures, open symbols; Spitsbergen Shelf recaptures, solid symbols. South East Barents Sea recaptures omitted.

independent—marked fish are caught during normal fishing –it is comforting to see that a similar depth pattern is indicated. This is added support for assuming that the behaviour of a marked population may be taken to be typical of the remainder of the stock –except for a short period immediately after marking. It was found during the cruise of August 1954 that when fishing for cod in the normal depths, i.e., 120–60 fm, the majority of cod suitable for tagging, i.e., those swimming quietly at the bottom of the tanks, were found to have

(a) ruptured air bladders and (b) ruptured body walls, through which the gas had escaped whilst the catch was compressed in the codend. This would almost certainly ensure that a released tagged cod would sink to and remain on the bottom until the air bladder wall had healed, unless the liver were abnormally well supplied with oil (Taylor 1922). Since it would probably take less than a month it is a further reason for treating the recaptures within the first month with some suspicion, i.e., fish were caught because they had been tagged and were therefore more vulnerable. As will be seen later, it is possible that the absence of an adequate buoyancy mechanism may prejudice the tagged cod's chance of denatant migration during the period when its air bladder is healing and this may, at least in part, explain the apparent slowness of tagged fish to leave the area of tagging. Its impaired buoyance may also be expected to reduce the fish's chances of feeding normally on the bathypelagic food organisms, especially if the latter also make diurnal vertical migrations which the cod would also be expected to make in the course of its search for food.

In the early months of the year, at the approach of the spawning season, the deep recaptures are those made, mostly by trawlers, in waters approaching the Norwegian Coast. A few weeks later, during the spawning fishery at Lofoten, it will be seen that many of the cod are recaptured from pelagic shoals—by the Norwegian purse seiners and hand lines in the Vestfjord—at depths of between 30 and 80 fathoms. Thus the mature fish have two periods when they are found at shallow depths, whilst the immatures are restricted to the shallow period of late summer. The importance of this observation is discussed in a later Section.

SECTION V
LIGHT AND FEEDING

As early as 1890 Bateson, at Plymouth, classed the cod as a visual feeder and went so far as to delimit its feeding period to the hours of daylight. This was also found by Zadulskia and Smirnov (1939) though the hours of feeding varied with the season. The type of food, mainly pelagic and active, found by Brown and Cheng (1946) to be taken by the Bear Island cod and its well-developed optic lobes (Muir Evans 1935) are also pointers to the cod's primarily visual feeding habit. It follows, therefore, that except when organisms are luminescent, e.g., Beröe and euphausiids, a certain level of illumination is required for feeding. Whilst this was mentioned in the Russian work referred to above (1939) no data were included in the paper.

The daylight of the Bear Island and similar latitudes differs from that of lower boreal latitudes both in relative intensity and also in its diurnal intensity changes. Thus, whilst the cod population of the North Sea experiences alternating daylight and dark during each 24 hours throughout the year, the Bear Island cod have a period of three months (early November to mid February) when even at midday there is civil twilight—sun centre on, to 7° below horizon approximately—which gives insufficient light to penetrate to the seabed. This is followed by a period of alternating light and dark in which light penetrates progressively deeper for an increasing period each day. During the subsequent three months, approximately, there is sufficient daylight to reach the bulk of the cod population during the whole 24 hours, taking into account their annual depth change already described.

Such basic differences in availability of light might be expected to produce differences of behaviour in the two populations. There is no evidence, however, that the Bear Island cod are seeking an optimum light intensity, in contrast with other or ganisms which carry out diurnal vertical migrations (Cushing 1951).

Feeding

Several different indices of feeding have been developed by many workers in their attempts to follow a feeding cycle. Some have been more satisfactory than others. In this paper the

simplest possible method has been adopted and use has been made only of a readily observable fact—the emptiness of a cod's stomach. This is really the reciprocal of feeding and has some limitations—thus, whilst a large cod containing three euphausiids is obviously not 'feeding' in the normal sense, it has not been classified as 'empty' for the purposes of this analysis. It has merely 'eaten'. Therefore in using the percentage occurrence of empty stomachs during the year, there is, throughout, an overestimate of feeding.

Log book entries dealing with stomach contents usually classified the overall feeding of the samples handled into Nil, Light, Moderate or Heavy, as well as logging the stomach contents of individual cod. The limitation of the method should however be borne in mind when consulting Fig. 29, which represents the mean values throughout the year obtained

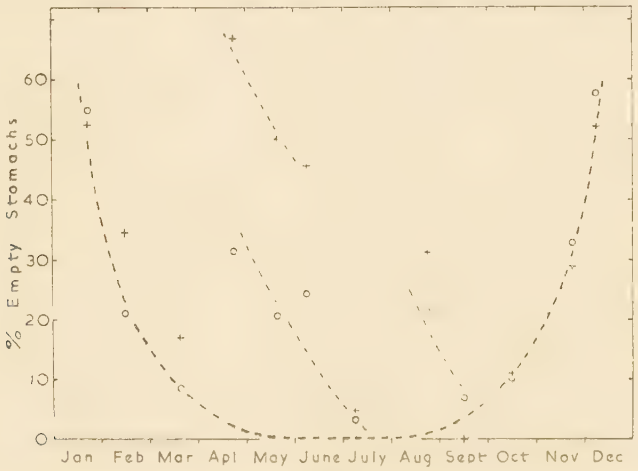

FIG. 29. *Annual feeding curve. Percentage of cod in* ERNEST HOLT *samples with empty stomachs—all cruises* 1949–1955.

Two depth ranges: circles = 100 fathoms or less; crosses 150–250 fathoms.

from 11,623 stomach contents observations, and extending over six years.

It will be seen that, by mid February, although the level of feeding was logged mostly as 'very light', the percentage of cod containing some food had reached the high figure of approximately 75 per cent, whilst by the end of March only 5 per cent of the cod sampled were empty. Whilst there was a small difference in feeding between fish from the two depth ranges selected, 120 fathoms or less and more than 120 fathoms, at the other end of the feeding period, October onwards, the difference appeared to be insignificant.

It must be stressed that the HOLT's sampling in January, February and March was restricted to the Bear Island Bank in depths down to 180 fathoms.

When the developing heavy Bear Island fishing was sampled in late April, May or June, i.e., when the major part of the immature population was approaching or had reached the Bear Island Bank, the deeper hauls invariably contained more empty fish than those from the shallower depths. (Fig. 29.) Fig. 30 shows the effect of depth upon cod feeding on euphausiids (Cruise III, ERNEST HOLT May 1955). It was evident that the shoals arriving at the Bank in these later months were different shoals from those sampled earlier on the Bank.

Low feeding from deeper hauls was also the experience from cruises later in the year to Hope Island and Spitsbergen, even in August and September (Fig. 29). In both these areas the samples contained a relatively high proportion of spents (first time spawners, as judged by their otoliths, which had a wide hyaline zone on the edge and, in most of the August samples, no current opaque zone at all). These fish appeared, from their feeding condition, to have arrived on the shelf only very recently as separate shoals from deep water—they were well below the mean depth curve level. The reason for the higher incidence of empty stomachs in the deeper hauls is thought to lie possibly with the vertical migration of the food organisms—the commonest on the west of the bank is *Euphausiia inermis*—rather than

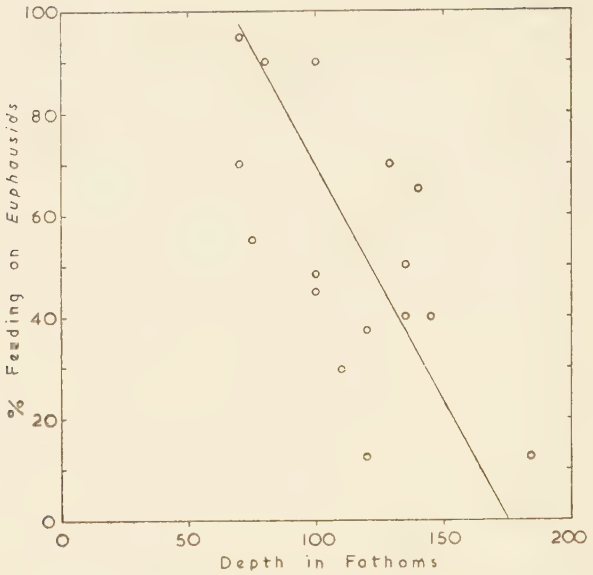

FIG. 30. *Percentage of cod containing Euphausiids, in* ERNEST HOLT *samples, from different depths (Cruise III April/May* 1955).

with the absence of sufficient light for feeding at that time of year. *E. longicaudata* was also taken but in small numbers and confined to deep water only. There are some irregular opportunities for feeding amongst herring shoals around Bear Island in October, mostly to the west. (Cruise VIII 1950, September 25th–October 18th).

It may be inferred, therefore, that the cod population reaches the Spitsbergen Shelf in a series of shoals and groups of shoals over a wide range of time. It has been seen that some of the codling of the category 'Small' winter on the bank. The 'June' fishery contains medium sized fish—almost 100 per cent immature—whilst the larger spents reach the grounds later still—late June in the 1952 marking experiment south-south-east of Bear Island, but usually July and, at the more distant feeding grounds, such as Hope Island and Spitsbergen, even as late as August and September. These latter must experience a very short feeding season, which according to the Feeding Curve has virtually ceased for all length groups by October/November. The short period allowed for feeding, caused by the length of annual migration to the spawning grounds, may be expected to contribute to the narrow opaque spawning zone described by Rollefsen (1933) and Fig. 29 should therefore be seen in conjunction with Fig. 26.

The timing and symmetry of the mean Feeding Curve points to light being the overall factor limiting feeding in these latitudes. Although no continuous sampling has been carried out in the SE. Barents Sea, the earlier and longer feeding season reported by Zatsepin and Petrova (*ibid*) is thought to be related to the longer period of adequate illumination at the lower latitude—some 300 miles south of the latitude of Bear Island—and to the shallower water of the whole area, which allows light to penetrate at an earlier date to the bottom shoals wintering in approximately 160 fathoms (290 metres) (Saetersdal 1956).

Quantity of Light on the Bottom in Latitude of Bear Island

There is a further aspect of light penetration which must now be discussed in connection with the siting of the fisheries carried on in the vicinity of Bear Island.

It has been shown that the cod population on both sides of the Spitsbergen Bank is found in progressively deeper water as the winter approaches—from September onwards. Table 3 gives the mean annual and diurnal values of light available for penetration through the water column, at approximately 73°N. These data are derived directly from Mosby's

TABLE 3

Mean Values of Light, all frequencies, available for penetration at surface (73°N) in Lux (M.Cs)

Hour	*February*	*March*	*April*	*May*	*June*	*July*	*August*	*Sept.*	*October*
1				2,092	7,672	4,185			
2				3,488	9,068	4,185			
3			(698)	4,882	12,555	5,580	1,395		
4			2,092	9,765	15,345	7,672	4,185		
5			6,278	15,345	20,228	11,160	6,975		
6		(1,395)	11,858	23,715	23,018	17,438	11,160	2,790	
7		4,185	19,530	29,992	30,690	23,715	16,042	6,975	
8		9,068	27,202	37,665	34,178	32,085	20,228	11,858	
9		13,950	32,782	41,850	39,758	37,665	25,110	15,345	2,790
10	2,790	20,228	41,850	50,220	46,035	43,245	30,690	20,228	6,278
11	5,580	25,110	47,430	54,405	49,522	48,825	36,270	23,018	9,068
12	6,278	26,505	48,128	55,102	48,128	51,615	36,270	24,412	10,462
13	5,580	25,110	47,430	53,010	48,128	50,918	34,875	23,018	8,370
14	3,488	22,320	42,548	47,430	45,338	47,430	31,388	19,530	5,580
15		16,740	36,968	41,850	41,850	42,548	27,900	15,345	2,790
16		11,160	29,295	36,270	37,665	38,362	23,018	10,462	
17		5,580	22,320	28,598	32,085	30,690	18,135	5,580	
18		(2,092)	13,950	21,622	27,202	24,412	12,555	2,092	
19		(698)	6,975	13,950	21,622	19,530	6,975		
20			2,092	9,068	17,438	14,648	4,185		
21			(698)	5,580	13,950	11,858	1,395		
22				3,488	10,462	7,672			
23				2,790	7,672	5,580			
24				2,092	6,975	4,185			

(Mosby's observations in the MAUD 1918–1925. Blue-green light would represent approximately 15% of these values.

observations in the MAUD (1932) in this approximate latitude—73 N—but further east, off the Siberian Coast. The original observations were given in the form Cal/cm^2/hour and have been converted to Lux (or International Metre Candles) blue/green light of between 4800A and 5500A which forms approximately 15% of the total light at the surface. It is possible that a further 10% reduction for reflection (Clarke 1954) should be allowed for, especially for the periods of low sun altitude. It is, however, not the aim of this paper to do more than establish the order of light intensity from existing data and it is hoped that actual bottom values will be obtained later.

During the July cruise of the ERNEST HOLT in 1953 it was observed that a reduction of 1 log unit for each 35–40 metres occurred in green light 5300A on the banks in Arctic water (Corlett, unpublished). Over deeper Atlantic water, penetration was rather less and was approximately 23–30 metre/log unit. In March/April 1956, however, rather greater values were obtained over deep Atlantic water 130 nautical miles south-south-west of Bear Island. Trial observations to 60 metres were obtained with a photomultiplier apparatus and gave a reduction of 1 log unit per 25–30 metres for the first 30 metres but below this depth water was far less turbid—1 log unit per 60–70 metres. This value is assumed to persist to the bottom. The four series of observations are given in Fig. 31. Whilst the results may not be strictly comparable with the earlier observations, a lower turbidity would be expected in the Atlantic water at that time of year, i.e., before the plankton outburst.

If it be assumed that a reduction of 1 log unit occurs, at an intermediate figure, say, 40–45 metres; and the depth of the shoals—from the extrapolated part of the depth curve (Fig. 26) - is 230 fathoms, or 420 metres, then the value of the light intensity reaching them will lie between 10^{-10} and 10^{-11} × surface value; using the data from Table 3 this would be of the order of 10^{-7} to 10^{-8} Lux in March. The threshold value for light response of *Lepomis* obtained by Grundfest (1932a) was 10^{-6} millilamberts or 10^{-9} Lux. Despite the two visual pigment systems found in fresh water and marine fish (Wald 1949) it is reasonable to assume that the sensitivity of the cod eye will not be lower than that of *Lepomis* and that the cod will react to comparable levels of light intensity. Thus towards the middle or

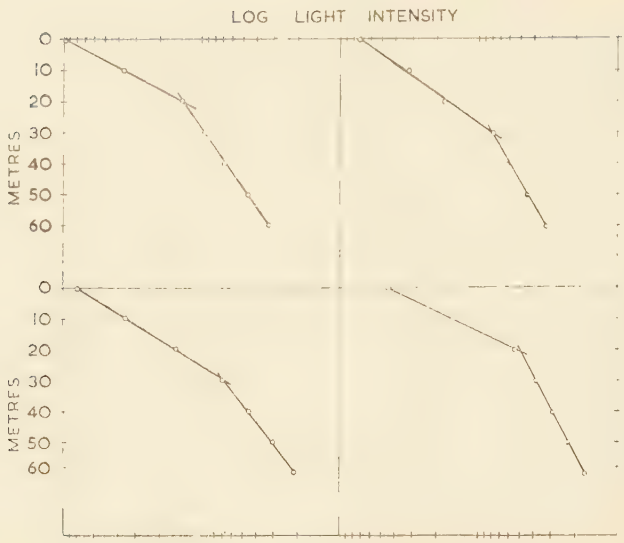

FIG. 31. *Light decay curve, 18th April, 1630-1712 GMT, 1956, by R.C.A. Photomultiplier apparatus.* 72° 28′ N 16° 30′ E.

end of March light at the bottom in 230 fathoms (420 metres) would be sufficient to initiate a response in cod of the wintering shoals during a short period at mid-day (local time). Likewise from the beginning of November onwards, there would be insufficient light, even at mid-day, to reach the bottom and the shoals must be considered to be entirely without light during this period of November to February when there is only civil twilight at noon.

Schüler and Krefft (1951) have shown that herrings and some gadoids (whiting) react to artificial light at night by changing the level of the shoal recorded on the echo sounder. Richardson (1952) has carried out similar work on herring and pilchard, and also reported the formation of a shoal on the sounder paper, after the switching on of the light source, in an apparently 'empty' sea. As far as the writer is aware no work has been published on the effect of daylight on deep water demersal fish.

In the absence of such experiments with artificial light and echo sounders in the Barents Sea, indirect evidence from Research Vessel observations and reports from trawlers must be relied upon for what is thought, by the writer, to be evidence of similar 'light reactions'. Fishing on a given bank may be reported as being 'daylight' or 'dark' fishing at different times of the year, implying that the heaviest catches were obtained during the daylight or dark hours respectively. These reports are often at first sight contradictory; for instance during cruise III 1956 (on ground 27th March–19th April) the ERNEST HOLT was in W/T touch with trawlers fishing the south-south-west and south-west Bear Island Grounds, and also with the Norwegian Research Vessel G.O. SARS in the Vardø Bank area. The trawlers at Bear Island were fishing in depths down to 240 fathoms, though a few were on the bank in water up to 150 fathoms (see Fig. 26). Trawler catches from the deeper water were reported to be heaviest during the dark hours. On the other hand, echo sounder records from the G. O. SARS in the shallower South East Barents Sea showed the cod shoals off the bottom during the dark period but on the bottom during the daylight hours. (Saetersdal 1956.) The South East Barents Sea fish were, however, probably feeding on capelin or herring shoals (Zatsepin & Petrova, *ibid*) whilst the Bear Island shoals from deep water were not feeding. Unfortunately, weather conditions experienced during the cruise frustrated all attempts to obtain echo sounder records on the ERNEST HOLT for the Bear Island area.

An analysis of all stomach contents observations was made for the years 1949–1955 in an attempt to determine whether a diurnal feeding rhythm could be established. The data proved inadequate for analysis on a monthly basis because of the relative infrequency of

observations made during the entire 24 hours. However, by arranging the data in three-hourly means, and by quarters, it was possible to obtain results for two depth ranges—0 to 100 fathoms and 150 to 250 fathoms, although the July/September quarter had only sparse information for the deeper range, because of the annual depth distribution of the cod already described. These results are given in Fig. 32.

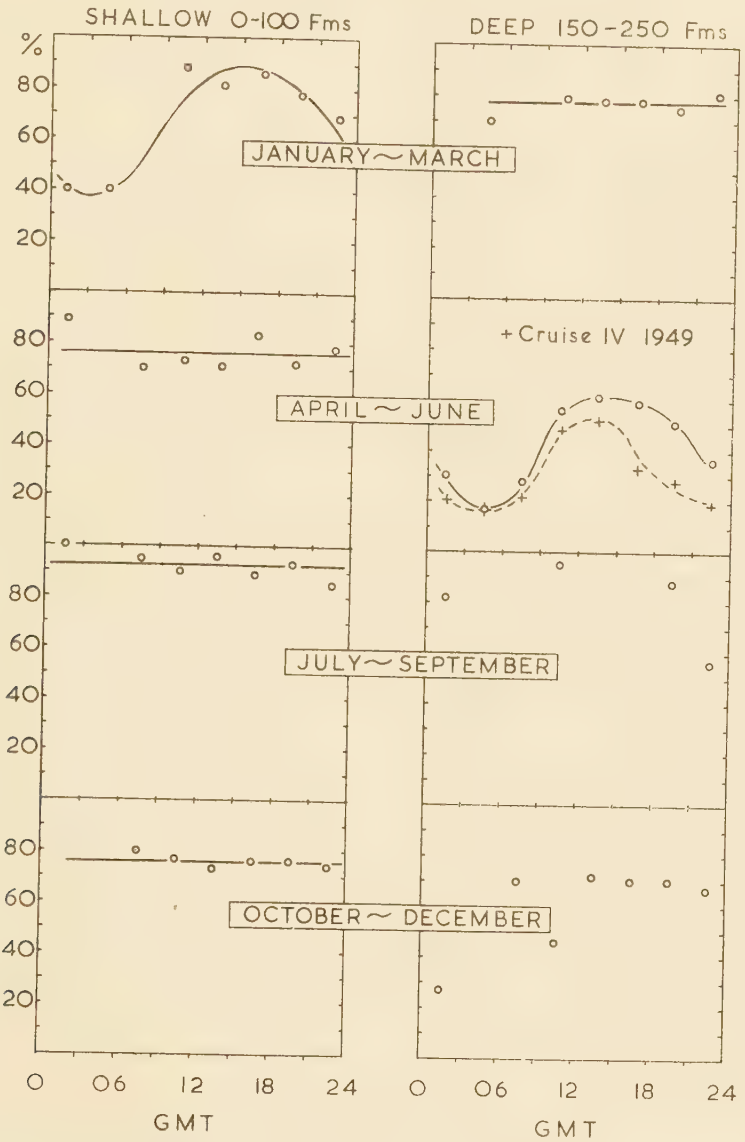

FIG. 32. *Diurnal feeding of cod. Percentage of cod containing* some *food in stomachs.*

Data arranged by quarters for two depth ranges: 100 fathoms or less and 150–250 fathoms.

It will be seen that, for the shallower depth range, the first quarter showed a diurnal rhythm in feeding. For the rest of the year the percentage feeding reached a peak in the July–September quarter, but in no later quarter did a diurnal rhythm of feeding emerge.

For the deeper water, the adoption of the diurnal feeding pattern was delayed until the second quarter and from one single cruise, which was confined entirely to deep water of approximately 200 fathoms in April/May 1949 (see also Lee): the diurnal pattern emerged

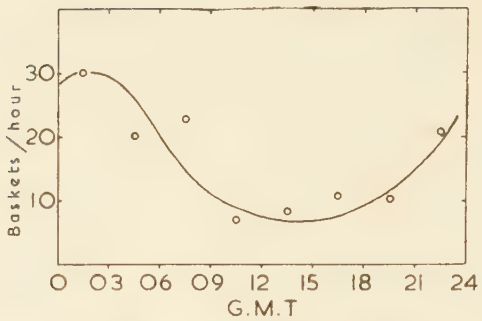

FIG. 33. *Diurnal vertical migration. Number of baskets of cod caught per hour during the 24 hours.*

Mean of 51 hauls by ERNEST HOLT April/May Cruise IV 1949. Time = GMT: local time = GMT + 1.

clearly and also the peak feeding period was shorter than the quarterly mean. The implication is that the greater depth of water delays daylight penetration until early in the second quarter approximately, and that thereafter the sortie from the bottom becomes progressively longer with the increasing daylight. This is also borne out by Fig. 33 which is the mean catch curve for the 51 hauls made in the April/May 1949 cruise in deep water.

It should be noted that times given in both curves are G.M.T. Local time was G.M.T. + 1 approximately—hence the displacement of the mean curves to the right.

There is indirect evidence, therefore, that penetration of daylight is responsible for the change in behaviour of the cod shoals and causes them to leave the bottom and to become diurnally pelagic, early in the year, even in depths of more than 200 fathoms. The length of time during which the cod are pelagic each day would increase with increase in intensity and duration of penetration. The importance of this is discussed, with the periodicity of water movements of the West Spitsbergen current, in the following Section.

Of interest is the fact that in Fig. 32 there is no recurrence of a diurnal rhythm of feeding after the mid year—the writer would hesitate to draw any inference from the deep water data in the July–September quarter since the number of observations are small. This figure might be taken as suggestive of a lower feeding intensity during the darker hours. It may be, however, that the data are insufficiently sensitive because they were based on incidental observations—the stomachs examined were those derived from age-determination samples and not from stomach samples designed to answer this particular feeding problem. There can be little doubt, on the other hand, that the importance of daylight is such that it limits feeding both at the beginning and the end of the year. It is considered possible that the apparent breakdown of the diurnal feeding pattern at the latter end of the year may be related to the operation of a new factor taking over from light and initiating the return migration to progressively deeper water.

FAT RESERVES

By the end of the feeding season it is a common observation that the liver has increased in size and takes up a large proportion of the body cavity. In the June shoals, the liver is small and shrunken and barely worth saving for oil. It was thought, therefore, that a study of the seasonal fluctuation of oil content of the liver might determine whether exhaustion of fat reserves took place in winter and thus prevented the immature cod from reaching the spawning grounds visited by the matures.

It was not possible to carry out the extraction of fat at sea and on the advice of Dr. T. Lovern of D.S.I.R., Aberdeen, it was decided to collect samples and preserve them in 2 per cent formalin for extraction on return to the laboratory. Small samples, 10 each of mature and immature cod livers, were preserved in this way and in addition small flesh samples of 20–30 gm were made from the same fish. Extraction was by Soxhlet apparatus after maceration and, in the case of the flesh sample, digestion. Fig. 34, which gives the

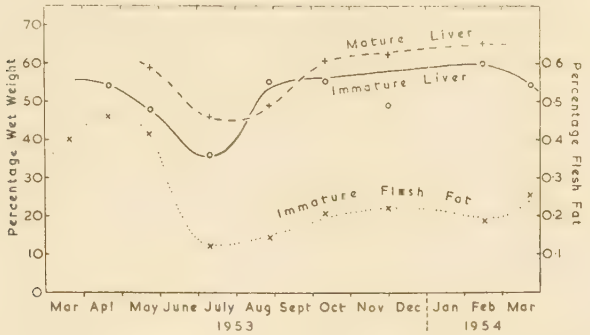

FIG. 34. *Annual fluctuations in liver and flesh fat of cod from Spitsbergen Shelf only*, 1953–1954.

percentage wet weight of liver and flesh fat, is put forward tentatively, because in using the preservation technique a few samples deteriorated in storage—thus after a period in storage of up to four months the March 1954 sample had to be rejected and replaced by one collected in March 1955. It is thought that the low value obtained for the 1953 November sample was due to poor storage conditions when insufficient formalin was added to some of the livers to cover them completely.

Sampling was confined to the Spitsbergen Shelf between February 1953 and March 1954. Mature fish were, therefore, absent from the Shelf during the spawning and migration periods.

A number of interesting points arise from the results. Firstly, the timing of the immature cod's minimum fat values, both liver and flesh, is such that depletion of fat reserves could not limit the southerly migration of the immature shoals, which stops short of the spawning grounds reached by the adults. On the other hand it would appear that the diurnal vertical migrations carried out in the period immediately prior to the shoals' arrival on the June fishery, when feeding is very light, depletes the fat reserves to a level where the fish are at a physiological minimum. It provides a reason for the very poor quality cod of the June shoals—which, in the 1952 tagging experiment, caused more than a 75 per cent. rejection of the cod caught. They were in an almost moribund condition.

The small but persistent increase in percentage wet weight of liver fat occurring after the end of the feeding season is thought to be dependent upon the method of presentation of the data—as a percentage. Had entire livers been used throughout and fish/liver weight ratio been obtained, the apparent anomaly would probably have been eliminated.

In terms of observed timing of migration the two curves for the immature cod may be interpreted as showing a transfer of fat from liver to flesh from September onwards to meet the demands of their active migration to deep water. The return of daylight to the latitude of Bear Island of an intensity sufficient to penetrate to the cod shoals, and their vertical migration response, depletes reserves to a minimum in June for the immatures, and July for the matures, when they return to the Shelf after spawning.

SECTION VI
DISCUSSION

MIGRATION—THE GENERAL PATTERN

FROM the results outlined in the earlier sections it is considered that the mechanism which effects the annual distribution of the cod does not depend upon one factor alone, or one factor operating all the time, but upon the interaction of a primary external factor—water movement—with a change in behaviour of the cod, the change in behaviour being dependent, initially, upon a second external factor—light. This hypothesis is developed below.

Water Movement

Warm water from the North Atlantic flows as the Atlantic Current northwards along the West Coast of Norway and enters the Barents Sea as the eastgoing North Cape Current. This sweeps in a broad band along the north Norwegian Coast and branches into two streams from East Finmark towards Novaya Zemlya and along the Murman Coast. There is a further branch, unnamed and ill-defined as a current (Knipovich 1905), but with a reasonably well defined 'front' to the east, which skirts the western edge of the Central Ridge and travels over the Bear Island Channel on a broad wedge towards the Hope Island and Great (Green Mud) Banks.

In addition, the Atlantic Current continues northwards as the West Spitsbergen current, along the steep western edge of the Spitsbergen Shelf, before it also turns eastwards, north of Spitsbergen.

These are the main warm currents which provide and, by their fluctuations, regulate, the bulk of the cod's environment in the Barents Sea. They extend, in the main, from surface to bottom over most of their length and in the case of the West Spitsbergen Current, water of 3° to 4°C may extend to 600 metres (330 fathoms) at the edge of the Continental Shelf. (Lee *ibid.*)

FIG. 35. *Spread of warm Atlantic influence over the Spitsbergen Shelf, August* 1954. *Inset of June observations for* 1952 *and* 1954.
Only 2° to 4° bottom isotherms are shown.

On the banks cold water, polar in origin, is found on the Spitsbergen Shelf, as the Bear Island Polar Current and the East Spitsbergen Current. Between the warm and cold currents lies a front or temperature gradient which may vary in position from year to year (Rasmussen 1949) and during the year as periodic transgressions of warm saline water occur and extend over the major part of the Shelf. (Fig. 35.)

Lee (*ibid*) has shown that for the years 1949 and 1950 there were two major increases in water transport in February and July in the West Spitsbergen Current and further work (Lee & Hill in press and Fig. 36) has confirmed that the major influx into the area takes

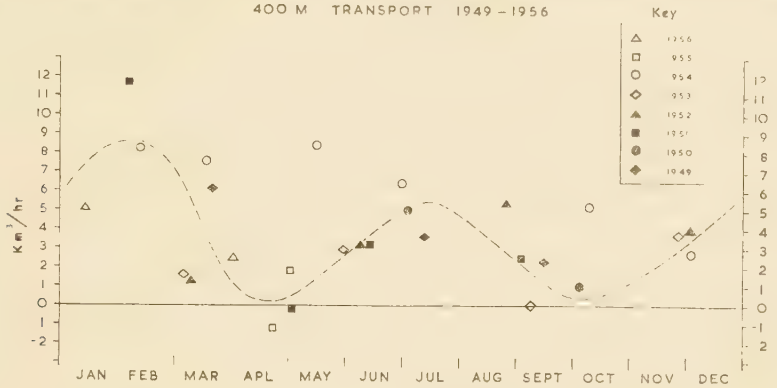

FIG. 36. *Annual pattern of water transport, West Spitsbergen current.*
From data kindly supplied by A. J. Lee and H. W. Hill (Hydrographic Section). Curve drawn by eye—G.C.T.—neglecting the unusually high May and October values obtained in 1954.

place early in the year (January/February). A second influx takes place in June/July/August. Low transport values obtain in April and are again low in October, whence they rise towards the end of the year. Variations occur, of course, from year to year.

The Wintering Migration

It has been seen that the trawlers fish progressively deeper as winter advances, that is, the cod are found in winter in deep water off the bank, which, on the west side of the shelf, is the water of the West Spitsbergen Current. (Fig. 26.) From the feeding curve, Fig. 29, it was seen that feeding diminished rapidly after the middle of October. This is thought to be due to the cod leaving the shallower feeding banks, i.e., of depths around the 100 fathom contour, but it is possible that reduction of daylight is, at least in part, responsible for the lowered feeding activity.

At this period daylight is insufficient to reach the seabed at the depths at which the cod are found. In the absence of light the fish are presumed to be on the bottom—there is no evidence to suggest that they are pelagic at any time during the dark period, November to February. The fact that no cod echo traces have been recorded despite fishing rates of up to 200 baskets per hour suggests that the fish are probably within a fathom or so of the bottom and hence below the limit of discrimination of the paper recorder (Cushing & Richardson 1955). Catch per unit effort rises from October onwards (Fig. 4), which implies an increased density on the ground.

It must be assumed, therefore, that the fish are on or close to the bottom, either in tactile contact or close enough to the bottom to obtain stimuli therefrom. In this position they would become orientated by the movement of the water over the bottom—a widely known reaction (Fraenkel & Gunn, 1940), i.e., they swim either at a speed sufficient to prevent their being transported backwards over the bottom or they swim actively forward against the current. From tagging results of the 1951 and 1952 experiments the latter is undoubtedly the case. (There would also appear to be evidence from the work of Davidson *et al* (1943) on mature salmon, that increased water flow stimulated upstream migration.) The extensive work of the Norwegian laboratory shows that adult cod reach the spawning grounds at Lofoten from grounds downstream, whilst the ERNEST HOLT releases demonstrate that the immature cod also swim actively against the deep current in the late months of

the year. Contranatancy is not, therefore, confined to mature fish but takes place contemporaneously in adults and immature alike and at a period of maximum water flow (Fig. 36). The fact that no northwards displacement of the fish occurs in this period of darkness– November to February inclusive –justifies the assumption that the fish are on the bottom and not pelagic.

A further observation, relevant at this point, concerns the mechanism whereby the density of the shoals increases. During the feeding months of July to mid-October the catch per unit effort falls progressively (Fig. 4). It is assumed that the cod are dispersed whilst feeding. Large shoals break up and the cod are probably mostly pelagic. It follows that when the cod begin to leave the shallower parts of the banks there will be a gradual arrival of small shoals on the slopes of the shelf. Certainly catch per unit effort increases but does not reach the high values of the June figures. Two factors are considered instrumental in causing a concentration, both within the shoals and also an aggregation of these shoals to form larger shoals, which can give rise to the relatively heavy fishing observed in the dark months.

Firstly the cod enter the fringe of the West Spitsbergen Current, which moves northwards and which reaches its maximum volume transport—an index of velocity—in January/February. On entering the current the fish will, in the absence of light, automatically become reorientated and head into the direction of flow (rheotaxis, Fraenkel & Gunn, 1940). The depth and rate of flow are such that tidal flow would probably be masked, if not eliminated. (On the banks adjacent to the West Spitsbergen Current there is likely to be more variable water movement with possibly a counter current, i.e., southerly in direction.) If the cod's speed of swimming through the water remained constant, then a reduction in speed over the ground would follow, with a resultant reduction of the distance between successive shoals on entering the current. Furthermore they would tend to be reorientated at similar depths and near the interface of the West Spitsbergen Current and the "front" between the colder water on the bank. In other words these concentrations would tend to be associated with the hydrographic gradient between the two water masses. This was a feature reported by Lee (*ibid*). The difference in velocity, and possibly of direction too, between the water masses would therefore appear to be a concentrating factor.

Secondly, although there is no evidence of a light orthokinesis (Fraenkel & Gunn) in the cod it is thought that a basic speed of swimming in darkness is not an inconsistent assumption, which may also contribute to the concentration of the fish. The reduction in length of time each day, during which light would reach the shoals as they progress deeper, might thus, also reduce the average distance run per day.

Whilst further work is required to isolate the factor initiating the cod's depth change in September, it would appear to be related to the changing daylight and may well be an internal change reversing their phototaxis. Devold (1955) describes the deepening of the mean depth of the herring shoals of the Atlanto-Scandian stock after mid September. After spending the summer near the surface, they begin "to dive down during the day into the cold water . . . rising into the warm water towards evening". Here there would appear to be a reversed phototaxis, as alternating daylight and dark returned to the area. Other factors, both external and internal, require further investigation.

The Return to the Banks

When daylight of sufficient intensity returns to the area and penetrates to the depths at which the cod shoals lie, a change in behaviour takes place (Figs. 32 and 33). The cod in the deep water exhibit a phototaxis and become detached from the bottom for progressively longer periods each day. However, at this time volume transport is decreasing towards the annual minimum of April (Fig. 36). There is therefore little or no northerly displacement of the shoals, in normal years. For example, in April 1949 and 1956 commercial fishing was still centred south-south-west to south-west of the Island in water of between 200 and 240 fathoms—these depths, it will be seen, lie close to the extrapolated part of the depth curve (Fig. 26).

Between April and June, water transport increases in the West Spitsbergen Current and the centre of fishing moves north until it is, normally, west of Bear Island for the June

fishery. The reasons for the increased concentrations observed at this time are more difficult to explain, but may be associated with light conditions allowing a closer spacing between fish in the shoals, for, despite the higher winter water transport, Fig. 4 shows a lower catch per unit effort than in the summer influx when light is maximal. This is also a period when well-defined gradients are observed, with the shoals closely associated with the eastern boundary of the West Spitsbergen Current. The explanation of this gradient association during the second (summer) influx, requires further study.

At the same time as this northerly displacement of the cod population takes place, Fig. 26 shows that the maximum rate of depth change is taking place. It is reasonable to consider whether these two phenomena, water transport and depth change of the cod, are connected.

In the years when sampling from the ERNEST HOLT covered areas away from the immediate vicinity of Bear Island, there appeared to be evidence of an incursion of warm Atlantic water on to the banks via the NW. Gully and/or the Storfjordrenna. With continued increase in volume transport this warm water had spread over the greater part of the bank by August. Fig. 35 is of the August Cruise 1954 but shows, as an inset, the bottom temperatures in June 1952 and June 1954. Only the 2° to 4°C bottom isotherms are shown and these, in the inset, mark the beginnings of the incursion.

It follows that the cod contained in the water of the West Spitsbergen Current, and at that time diurnally pelagic, would be carried by the incursion up the Gully and into shallower water. An echo survey made across the NW. Gully in June 1952 found small numbers of shoals, presumed to be cod, at depths similar to those being fished on the banks south of the Gully. It is thought, however, that although some additional vertical impetus may be imparted to the cod by the water flow up the Gully and the Storfjordrenna, it would be minimised by the effect of the air bladder (Jones 1951 and 1952) and the need for pressure acclimatisation. The cod shoals may be expected, therefore, to lag behind the penetration of the influx, over the banks.

Whilst depth change on the western edge of the Spitsbergen Shelf may be affected by such a surge of water on to the bank, no such incursion has been observed on the eastern edge of the shelf, east of the SE. Gullies. None the less, W/T fishing reports indicate a comparable annual depth change (Fig. 36) for grounds east of the SE. Gullies, on the eastern edge as far as Hope Island and the Great Bank. It is possible that an extension of the tongue of warm water, frequently observed filling the SE. Gullies, could spread northeast over the banks as a wedge of warm water entering the cold. Even if this were so, and a mechanism occurred similar to that observed on the west, the coincidence of timing of depth change, if entirely passive, i.e., dependent upon the rate of penetration of the incursion, would be difficult to credit.

The general assumption is that, although a surge of Atlantic water may affect locally the rate of depth change, the annual vertical movement is an active one made by the fish and internally controlled. Its asymmetry in timing is due to the depth to which the cod shoals penetrate in winter and the delay of the correct stimulus —light —in reaching them. Evidence to support this hypothesis is available from echo surveys carried out in 1951 and 1953 at the eastern end of the Bear Island Channel and Hope Island Deep. Sounders of two frequencies (10 and 30 Kc) were used and on three consecutive cruises in 1953 it was possible to determine the order of size of fish responsible for two types of trace (Cushing and Richardson 1955). Small fish, probably capelin, were seen in the upper layers and larger fish, presumed to be cod, at a lower level (Plate 6). Both traces were clear of the bottom and were well away from the Hope Island Bank where they were to be expected at the time of those cruises. (July 1st–14th; August 22nd–September 4th; and October 8th–23rd 1953—on the grounds.) In this connection it must be noted that cod were found also on the bottom below these pelagic shoals, which did not, therefore represent the whole vertical spread of the population.

During the latter half of 1953 poor fishing on the east of the Spitsbergen Shelf was commented upon many times by the commercial trawlers and one of Hull's most experienced Distant Water Skippers, Mr. Charles Hogg, reported visiting the area on a number of trips and found no fish between the SE. Gullies and Hope Island.

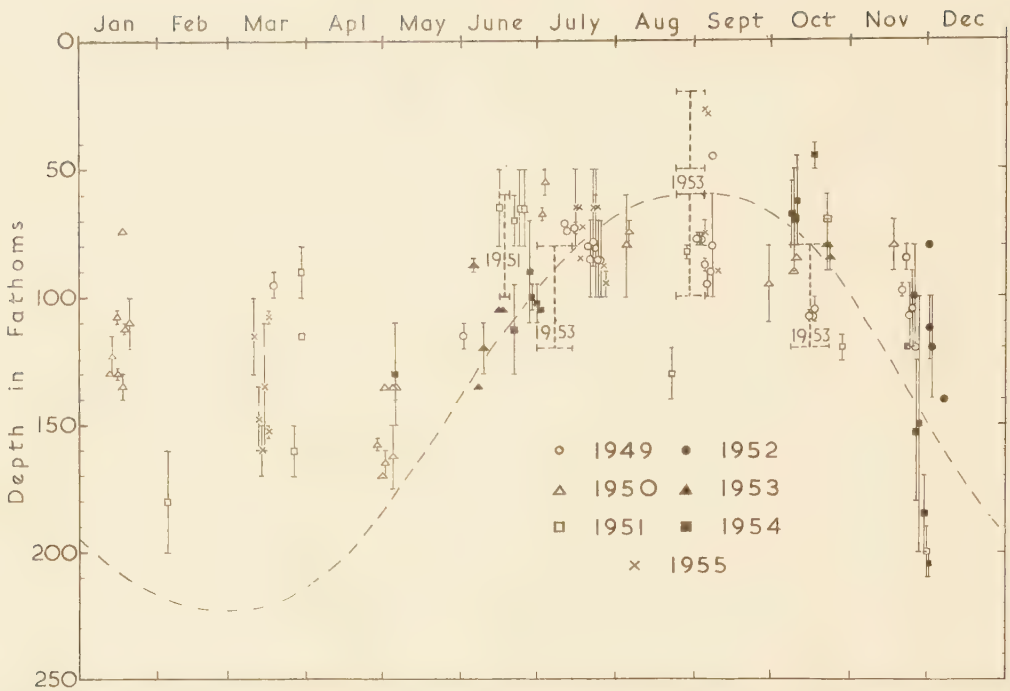

FIG. 37. *Mean annual depth curve of cod, Spitsbergen Shelf, East of* 21°E, *from commercial trawler W/T reports received by* ERNEST HOLT 1949–1955.

Dotted vertical brackets show spread in depth of pelagic cod shoals, derived from 1951 and 1953 echo surveys.

From the ERNEST HOLT's echo surveys, summaries of the vertical spread of the traces assumed to be cod are shown (Fig. 37) for the single cruise undertaken in 1951 and for the three cruises of 1953. Analyses of the echo traces were kindly carried out by Dr. Cushing and it will be seen that the spread of trace depth compares with that obtained from the cod fished on the banks, the mean curve of which is indicated (from Fig. 26).

The writer infers that the cod and capelin remained over deep water in 1953 without reaching the banks. It has been established, furthermore, (Lee & Hill, *ibid*) that 1953 was a year of rather low volume transport—apparently insufficient to carry the cod and capelin in their pelagic state to the banks normally reached when somewhat higher transport values obtain. The cod, nevertheless, carried out their regular annual vertical migration without reference to the bottom. This would appear to be a normal behaviour pattern and many reports have been obtained from trawler skippers fishing at Greenland and Iceland, that cod have been seen swimming and splashing at the sea surface, well above any banks. Rasmussen (1954) describes the Norwegian pelagic long line fishery for cod which is carried out each year at Greenland where lines are set from surface to approximately 70 fathoms (136 metres). In his analysis of catches he subdivided the total depth fished into four and showed that cod were caught in each depth bracket—although somewhat higher catches came from the lower half of the column fished. The average catch was 235 cod per 1,000 hooks in 13 to 57 metres; 306 in 57 to 92 metres; 352 in 92 to 128 metres; 348 in 119 to 136 metres. Bottom catches in summer (Rasmussen 1953) averaged 95 cod per 1,000 hooks, against 135 per 1,000 hooks set pelagically. It is known from other trawler reports that fishing in winter at Greenland, particularly on the more southerly banks and the Cape Farewell Grounds, is carried out in depths down to 280 fathoms (512 metres) but there are insufficient data available to determine the timing of the Greenland cod's annual depth change.

It is appropriate to consider, at this point, how the cod, when so largely pelagic, may penetrate from one water mass to another. For example, in an earlier section an association

was established between cod caught in cold water—of approximately 0 C —on the Hope Island grounds, and their possession of the 'split' type of otolith. How would cod, at depths below those which could allow a 'light compass reaction' (Fraenkel & Gunn, *ibid*) to take place, move horizontally to enter a different water mass ? The steady annual progression in depth suggests that large scale random horizontal movement may be eliminated. Catch per unit effort is almost maximal in July and August so that the fish are necessarily in large numbers, in shoals.

At this time, water transport is high and turbulence may be expected to cause mixing at the interface of the two adjacent water masses and with a distinct possibility of transfer of a small proportion of the contained fish, to the region of mixed water. This may be the initial stage. It is thought, however, that the main mechanism is the result of interaction of two phenomena: (a) the incursion of warm water from the western edge of the Spitsbergen Shelf and (b) the pelagic feeding/bottom resting phase of cod during the feeding season (Ellis, *ibid*). This is the writer's interpretation of the structure of the summer cod shoals, wherein some are seen by sounders to be pelagic, whilst trawling may still produce relatively heavy catches. It would appear possible for the incursion from the west to displace the cold shallow water of the Bear Island Polar Current, south-eastwards into progressively deeper water to cover the lower slopes of the banks. Thus the shoals resting on the bottom, originally feeding in warm upper water layers, may either enter cold water on approaching the bottom or become overlaid by the displaced cascading cold water mass—they become engulfed by the cold water and do not swim actively, horizontally, into it.

More study is required to provide the detail behind the transfer of cod into cold water and the mechanism may be elucidated by the temperature/fish analysis being carried out independently. More data are also required concerning the periodicity and flow of the Bear Island Polar Current in order to determine the part it plays in the horizontal distribution of the cod towards the end of the summer feeding period.

It is also of interest, at this stage, to obtain an approximate estimate of the maximum distance over which a cod could be carried, entirely passively, by means of the water movement occurring during the summer influx. Various estimates of average surface speeds have been given for the Atlantic Current running along the NW. Norwegian Coast—10 to 15 nautical miles per day—whilst at Bear Island the maximum of 8 to 10 nautical miles per day appears reasonable (Arctic Pilot Vol. II).

It is necessary to make a number of assumptions: (a) that volume transport may be taken as an index of water speed; (b) that speed of water movement at the bottom –or 5 to 20 fathoms above bottom—is a substantial proportion of that at the surface; (c) that its speed at the summer maximum is of the order of 4 to 5 nautical miles per day; (d) that the rate of flow during the period April to October follows, approximately, the mean curve of the transport values (Fig. 36); (e) that tidal influence may, if anything, increase the horizontal displacement.

These assumptions would give maximum monthly displacements, excluding tidal effects, from mid April onwards of: April, 5: May, 45: June, 110: July, 170: August, 110: September, 35: October, 5: Total = 480 nautical miles approximately.

The most distant grounds normally fished commercially are (a) The Great Bank (Green Mud Bank), (b) Prince Charles' Foreland, (c) The Betty Bay Grounds and (d) The eastern limb of the Storfjordrenna.

These lie respectively approximately 360, 360, 300 and 300 miles distant from a hypothetical starting point 72° 30′ N 17° 0′ E. The north east-going unnamed current of the Bear Island Channel would probably not reach the speed of the West Spitsbergen Current and so might have a lower potential distance than that on the west coast of Spitsbergen.

It is known, of course, that the cod are not pelagic throughout the 24 hours, even during the midnight sun period, and tagged cod returns indicate a lower speed than the theoretical current speed. It is suggested that the difference depends upon the feeding behaviour of the cod, feeding pelagically but quiescent and digesting on the bottom, and upon the fall off in speed of current from surface to bottom.

Variations in transport values would obviously affect the horizontal distribution of the cod and contribute to the variations in the timing of a fishery associated with a given ground.

There would appear to be, none the less, ample horizontal water movement to produce the summer distribution of the cod by passive drift alone, without any active or directed swimming, other than required locally for the capture of pelagic food.

Migrations of Bear Island Cod in Successive Years

The structure of the typical Bear Island otolith shows that the first few years of life are spent in a constant type of habitat—presumed to be the warm stable conditions of the West Spitsbergen Current and its offshoots. Subsequent opaque zones laid down whilst the cod is still immature are, in approximately 65 per cent of the otoliths of the 'split' type, associated with a portion of the feeding season being spent in the colder conditions reached by means of the mechanism postulated above, both at Spitsbergen and Hope Island grounds. The writer infers that the cod has a more *easterly* distribution with age and there is some support for this from the tagging data. None of the 2000 cod released in the Hope Island area were returned from Spitsbergen grounds, whereas a small number of Spitsbergen releases were taken from Hope Island or approaches to Hope Island grounds, i.e., on the south-east edge of the Shelf.

Mature Cod

A large number of cod, which, because of size must be considered mature, have also provided evidence of this easterly trend with time. Since the first spawning season in which cod tagged on the Spitsbergen Shelf could have taken part, a total of 33 recaptures has been made in the SE. Barents Sea.

Results of Norwegian tagging of mature cod during the Lofoten spawning seasons (Dannevig 1947–1950) demonstrate a preponderance of easterly recaptures —approximately 73 per cent of the recaptures away from the spawning grounds were made in the SE. Barents Sea and only 22 per cent came from the Spitsbergen Shelf. None were returned from Spitsbergen. A small number were recaptured on the North Cape Bank and NE. and are assumed to have been on their way towards the Central and Great Banks, lying to the east of the Spitsbergen Shelf. It must be accepted that a differential distribution did, in fact, take place. Fig. 38 gives the total landings from the two regions, SE. Barents Sea

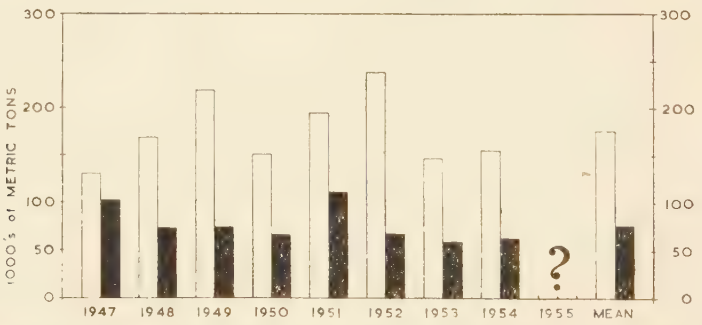

Fig. 38. *Total cod landings, excluding Russia, from Region I (South East Barents Sea) (White) and Region IIb (Spitsbergen Shelf) (Black) for years* 1947 *to* 1954, *and the mean annual landings.*

The landings are taken from the Bulletin Statistique and those for 1955 are not yet available.

(Region I) and Spitsbergen Shelf (Region IIb) for the years subsequent to the Norwegian releases, 1947–1954. It will be seen that although landings from Region I are higher than those of Region IIb, some 2 to 3 times, the difference given by the tag returns is of the order of 3·3 : 1. The higher value of mature returns from the SE. Barents Sea is therefore real. There is thus a recruitment of mature cod from the Spitsbergen Shelf to the SE. Barents Sea. This is also supported by Fig. 39, of Hull and Grimsby market measurements where the larger categories are better represented in Region I than in Region IIb. As this figure is a percentage composition, reference should also be made to the previous figure of

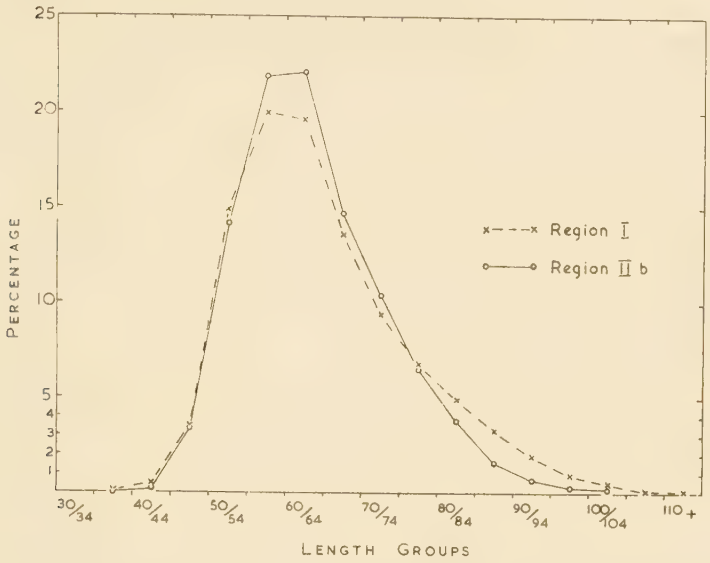

FIG. 39. *Percentage length/frequency curve of Hull and Grimsby market samples from Region I (South East Barents Sea) and Region IIb (Spitsbergen Shelf).*
Mean values for years 1951–1955.

landings from the two regions and to Fig. 4 of the catch per unit effort (100 hours fishing) for each region.

The explanation of this important fact is thought to be as follows. In addition to being caught on the main spawning grounds inside the Vestfjord, mature cod from the Spitsbergen Shelf are recaptured on the steep edges of the Continental Shelf of Norway from Malangen's Ground and Lofoten as far south as the old spawning ground of the Arcto Norwegian stock—Romsdal (Sund 1939). Dannevig (1947–1950) shows that the Norwegian Lofoten-tagged mature cod, returning in subsequent years to spawn, are restricted to more inshore regions of the Lofoten and Vesteraalen grounds and are rarely caught outside these areas, i.e., they are rarely recaptured on the deeper bank slopes offshore or as far south as those from ERNEST HOLT releases. It is to be expected that mature cod travelling contranatantly in the two main currents, Spitsbergen Shelf cod in the West Spitsbergen Current and South East Barents Sea cod in the North Cape Current, would reach the north-west Norwegian coast at different places. It is also to be expected that those in the West Spitsbergen Current would be further offshore and have a more southerly distribution than those from the more coastwise North Cape Current.

Sund (1939) showed that the age and length composition of the spawning shoals decreased at the eastern and western fishing centres of Kabelvåg and Verøy—the first-time spawners reaching these areas last. At the more central port of Balstad, however, the reverse took place. These observations may possibly be explained by the overlap of the spawning areas normally covered by the two populations from the Spitsbergen Shelf and the SE. Barents Sea.

Cushing and Burd (1957) explain the anomalous early arrival of the young maturing herring in the East Anglian fishery, long known from Hodgson's researches (1939), as being due to the presence of two spawning groups in the East Anglian shoals. It may be inferred from the length distributions of the shoals caught in the general spawning area that the two groups spawn on adjacent grounds.

After spawning in the sounds and fjords most spent cod would tend to be affected by the coastwise water movement which is the North Cape Current, rather than the more distant and offshore West Spitsbergen Current. Thus there would be a tendency for a larger proportion of the spents to be given an easterly distribution initially, before water movement fell to the seasonal minimum in April.

Fig. 28, showing the depth at which mature tagged cod were caught on the spawning grounds (open symbols) indicates that after spawning pelagically, the spents remain pelagic for some time. The precise length of this pelagic period cannot be ascertained from these data, but Fig. 40 underlines the importance of the branches of the North Cape Current

FIG. 40. *Bottom temperature survey of Barents Sea. Eastern half solid isothermal lines—December* 1953. *Western half—broken isothermal lines—January/February* 1954.

Superimposed are the recapture positions of the 1951 and 1952 Tagging Experiments (solid symbols) and Dannevig's, Lofoten tagged and recapture positions, 1947–1950, (open symbols).

to the distribution of mature cod. It is a composite figure of Dannevig's (1953) and the writer's tagging data superimposed on the bottom isotherms obtained in December 1953 (eastern half) and January 1954 (western half). The winter bottom isotherms are used in the absence of suitable summer cover of the area by the ERNEST HOLT. It must also be emphasised (a) that winter transport figures (Lee & Hill's data in Fig. 36) are higher than the summer values in the Spitsbergen Current and this is almost certainly true for the North Cape Current; (b) the 1954 transport values were above normal and it may be expected that this fact has influenced the December 1953 distribution of warm water and tends to exaggerate the summer extension.

The association between the major current and the distribution of the tagged cod recaptures, spreading from the deeper water over the shallower banks, suggests that the mechanism of distribution in this area also depends upon the pelagic behaviour of the cod during the lighter months.

Return Routes of Matures to the Spitsbergen Shelf

A certain number of ERNEST HOLT tagged cod recaptured in the Bear Island region can, by size, be assumed to have been spents. As it has been shown (Figs. 23 and 24) that the Spitsbergen Shelf cod arrive on the Norwegian Coast well south, it is reasonable to assume that after spawning, they reach deep water again when transport values are minimal and are therefore more likely to be in water destined to become part of the West Spitsbergen Current. Those from more northerly grounds would probably enter the North Cape Current.

Between these main return routes there appears to be a further important route which passes in a northerly direction from North Cape Bank to the region of Iversen's Bank. A number of returns were made from the region of 73°N 33°E approximately and northwards to Hope Island and Great Bank. According to Lee (personal communication) water movement in this area and over the Bear Island Channel is somewhat variable in direction at certain times of the year. The times of recapture of cod from this area, however, mostly May and June and December, suggest that when the two main currents experience their maximal transport values, there is also sufficient flow in this less well-defined current to influence the denatant and also contranatant migrations of cod.

It is also thought that it is by this route that cod with the Finmark (E) type of otolith may become detached from their normal grounds and procede northwards to reach the grounds of Hope Island and further east—hitherto their presence there was difficult to explain (Fig. 9). Corlett (in press) has also shown that bottom stage group 0 cod occur in this general region in significant numbers in October to December, i.e., after the summer water transport maximum.

The Effect of Differences in Water Transport Values on Cod Shoals

It has been seen that the transport values of 1953 were low in June. The effect of this has been discussed. In 1954 transport values were high throughout almost all the year. This latter case, it is thought, would have a two-fold effect. Firstly the mean speed of the cod shoals, swimming contranatantly, and their distance made good over the ground, might well be reduced, causing them to be delayed in reaching a given latitude or even preventing them from reaching their normal southerly limit. This, indeed, appears to have occurred in February 1954, when the writer was completing the second half of the bottom temperature survey of the Barents Sea (Fig. 40). Commercial vessels were then fishing on heavy shoals in deep water near the NW. Gully—a ground usually associated with November/December and also June fisheries. The strangeness of this occurrence was commented upon by several skippers, including Mr. Hogg. Only light fishing was encountered in deep water by the ERNEST HOLT south-west of Bear Island.

The secondary effect would occur as a result of their being restricted to more northerly grounds than usual. Thus, with the return of daylight the shoals tend to be displaced further north and at an earlier date. Norwegian fishermen reported catching cod in June 1954 off Bellsund–Spitsbergen. There is also some evidence (Fig. 37) that high transport values of 1954 and the more northerly distribution accelerated the depth change.

In 1953 the shoals were deep in late May—still 200 to 250 fathoms—and somewhat deeper than the mean curve in July and October. Being free of the interference of the bottom, this may be their normal, innate, depth range, whilst the timing and extent of the second Atlantic influx, in June, determines the pattern of the Spitsbergen Shelf fishery and the subsequent spread of the shoals on the banks.

SUMMARY

An attempt has been made to report on the picture of cod movements which has been built up gradually from the various data referred to above. The interpretation is, at this stage, incapable of rigid proof; its justification is that it fits a wide range of facts and has few ranged against it. It is now possible to see the pattern of the main facts and to put forward a generalised model of movement of the Arcto Norwegian cod stock as a whole.

The distribution of the two main types of otolith, found mixed on the more southerly grounds but largely separated with increasing distance from Bear Island, suggested fish advancing on the two sides of the Spitsbergen Shelf during the feeding season and returning to the general area of Bear Island in the winter. (Figs. 5–12).

The association of split zones with cold water in the second half of the feeding season and the sequence of opaque zone structures in the otoliths, suggests a west to east transference of cod with age; e.g., from west to east Spitsbergen grounds, or the west of the Spitsbergen Shelf to the east edge of the Shelf.

Evidence is also put forward to relate opaque zone formation to heavy feeding (Fig. 29).

Tagging experiments were carried out and confirmed the movement of advance in summer and return in late autumn of the Bear Island shoals (Figs. 15 and 20). It was demonstrated that such an advance could be brought about by a purely passive drift of the cod in the summer surge of the West Spitsbergen Current or of the offshoots of Atlantic water penetrating onto the banks. The factor initiating the return autumn movement is inferred to be related to changes in light intensity and in phototropism of the cod.

Tagging results demonstrate that the return to Bear Island and further south is a contranatant migration occurring during the winter maximum of water transport, and that contranatancy refers to mature and immature cod alike. An important recruitment of mature cod to the SE. Barents Sea takes place from the Spitsbergen Shelf population after spawning at the Lofotens. (Figs. 21 and 39.)

The overall annual light/feeding relationship is described (Fig. 29). Light and a largely pelagic way of life were associated seasonally with feeding activity, as recorded on board the ERNEST HOLT. Diurnal feeding with vertical movement was also demonstrated at certain seasons (Figs. 32 and 33), whilst the annual movement in terms of depth is well documented from commercial fishing information obtained by W/T or R/T during each research vessel cruise. (Figs. 26 and 37.)

It was inferred from seasonal estimates of liver and flesh fat that these food reserves were not factors limiting the southerly winter migrations of the immature cod (Fig. 34) although the diurnal activity related to the return of adequate light to the region, caused depletion of the overall reserve and gave a probable reason for the low physiological state and poor quality of the Bear Island 'June' fish.

So much for the facts. It remains now to put forward a synthesis of facts and conjecture in a plausible theory of cod movement in the Barents Sea cod population as a whole. This is seen as follows:

Water movement is responsible for the changes in distribution of the Arcto Norwegian cod, yet this is only a secondary effect of their changing behaviour in response to changing light conditions, which results in their primary annual vertical migration and their annual depth change.

Winter rheotactic or contranatant migration takes place on the bottom in the absence of light during the period of the annual water transport maximum.

Summer passive or denatant migration takes place during the lower summer peak of water transport, at which time the cod shoals are largely pelagic in response to light. They are thus capable of being displaced horizontally, relative to the bottom, by movements of the water mass containing them. Maximum horizontal displacement is not achieved because a portion of the shoal spends a part of each 24 hours on the bottom. All known geographical limits of fishing are well within this maximum distance. Variations in summer transport values will affect the limits reached by the shoals from year to year.

During the active rheotactic winter migration, larger fish will, other things being equal, tend to progress further than the smaller ones (although annual variations in water flow may well negate their increased swimming potential), thus reaching latitudes south of Bear Island. There, by the end of the winter and with the return of adequate daylight, they will be in a position to be displaced in an easterly direction towards the Hope Island area, by the summer surge.

Once mature and on the spawning grounds, they will tend to be displaced eastwards by the North Cape Current into the SE. Barents Sea on emerging from the Norwegian sounds and fjords. There is thus a recruitment of spawners from the Spitsbergen Shelf into the SE. Barents Sea grounds and whilst it is possible for the transfer of cod from the latter region to the Hope Island area to take place, the overall effect remains a west to east recruitment.

Distribution, therefore, is the resultant of interaction of changing behaviour with the cycle of movement of the water masses in which the cod are found.

Normally fish will tend to remain in their particular water mass but transference from one water mass to another may take place as a result of changes in behaviour. In the absence of water movement, horizontal movement will be of limited extent, but the annual depth change would be expected to persist.

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